AD-A115 888 TEXAS UNIV AT AUSTIN ELECTRONICS RESEARCH CENTER F/G 9/1
ANNUAL REPORT ON ELECTRONICS RESEARCH AT THE UNIVERSITY OF TEXA--ETC(U)
MAY 82 E J POWERS F49620-77-C-0101
UNCLASSIFIED AFOSR-TR-82-0502 NL

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Annual Report on Electronics Research at The University of Texas at Austin

No. 29

For the period April 1, 1981 through March 31, 1982

JOINT SERVICES ELECTRONICS PROGRAM

Research Contract AFOSR F49620-77-C-0101

May 15, 1982

ELECTRONICS RESEARCH CENTER

Bureau of Engineering Research
The University of Texas at Austin
Austin, Texas 78712

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Submitted by Edward J. Powers
on Behalf of the Faculty and Staff
of the Electronics Research Center

May 15, 1982

ELECTRONICS RESEARCH CENTER

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The University of Texas at Austin
Austin, Texas 78712

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ABSTRACT

This report summarizes progress on projects carried out at the Electronics Research Center at The University of Texas at Austin and which were supported by the Joint Services Electronics Program. In the area of Information Electronics progress is reported for projects involving (1) nonlinear detection and estimation and (2) electronic multi-dimensional signal processing.

In the Solid State Electronics area recent findings in (1) interface reactions, instabilities and transport and (2) spectroscopic studies of metal/semiconductor and metal/metal oxide interfaces are described.

In the area of Quantum Electronics progress is presented for the following projects: (1) nonlinear wave phenomena, (2) structure and kinetics of excited state molecules, and (3) collective effects in nonlinear optical interactions.

In the Electromagnetics area progress in guided-wave devices for the far infrared-mm wave spectrum is summarized.

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PERSONNEL AND RESEARCH AREAS

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Professor Rodger M. Walser, Assoc. Director

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PERSONNEL AND RESEARCH AREAS

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Kathleen Thrush, Chemistry
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*Denotes persons who have contributed to JSEP projects, but who have not been paid out of JSEP funds (e.g., students on fellowships).

PERSONNEL AND RESEARCH AREAS

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*Yihjye Twu, EE	Sudhakar Yalamanchill, EE
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Advanced Degrees Awarded

Joseph George Ambrose, EE, M.S., May 1981, "Laser Solid Interactions."

Hon-Son Handson Don, EE, M.S., August 1981, "Cross-Power Spectral Analysis of Nonstationary Data."

Nian-Chyi Huang, EE, Ph.D., May 1981, "Analysis and Synthesis of Linear Shift-Variant Digital Filters."

Chang-Huan Liu, EE, Ph.D., December 1981, "Applications of Algebraic and Approximation Methods in Nonlinear Estimation."

David Yi-Fang Sheng, EE, Ph.D., December 1981, "Heterogeneous Nucleation of Damage Structures in Crystalline Silicon by Picosecond 1.06μm Laser Pulses."

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PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

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*L. Frommhold, G. Birnbaum, "Collision-Induced Absorption and the Repulsive Ne-Ar Potential," submitted for publication.

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D. Hull and J. Speyer, "Optimal Reentry and Plane-Change Trajectories, accepted for publication in Journal of Astronautical Sciences.

J. Krainak, J. Speyer and S. Marcus, "Static Team Problems, Part II: Affine Control Laws, Projections, Algorithms, and the LEGT Problem," accepted for publication in the IEEE Transactions on Automatic Control.

*R.J. Mawhorter, M. Fink and B.T. Archer, "An Experimental Determination of the Vibrationally-Averaged, Temperature-Dependent Structure of CO_2," accepted in J. Chem. Phys.

M.H. Kelley and M. Fink, "The Temperature Dependence of the Molecular Structure Parameters of SF_6," accepted in J. Chem. Phys.

*K. Hsu and S.I. Marcus, "Decentralized Control of Finite State Markov Processes," accepted for publication in IEEE Transactions on Automatic Control (1982).

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*Chien-Yu Kuo and J.W. Keto, "Dissociative Recombination of Electrons in Electron Beam Excited Argon and High Densities, in press.

Y. Kim, J.A. Schreifels and J.M. White, "Adsorption of N_2O on Ru(001)," Surface Sci., in press.

H.-I. Lee, B.E. Koel, W.M. Daniel and J.M. White, "Water-Induced Effects on CO Adsorption on Ru(001)," J. Catalysis, in press.

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B.E. Koel, D.E. Peebles and J.M. White, "An Electron Spectroscopic Investigation of Coadsorbed H_2 and CO on Ni(100)," J. Vac. Sci. Tech., in press.

D.E. Peebles, J.A. Schreifels and J.M. White, "The Interaction of Coadsorbed Hydrogen and Carbon Monoxide on Ru(001)," Surface Sci., in press.

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J.A. Schreifels, J.E. Deffeyes, L.D. Neff and J.M. White, "An X-ray Photoelectron Spectroscopic Study of the Adsorption of N_2, NH_3, NO and N_2O on Dysprosium," J. Electron Spectry, in press.

*S.R. Federman, L. Frommhold, "Recombination of Hydrogen Atoms via Free-to-Bound Raman Transitions," Phys. Rev. A, to appear.

*P.D. Dacre, L. Frommhold, "Rare Gas Diatom Polarizabilities," J. Chem. Phys., to appear.

*A.B. Buckman, "Polarization-Selective Lateral Waveguiding in Layered Dielectric Structures," Journal of the Optical Society of America, to appear.

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TECHNICAL PRESENTATIONS

IEEE International Conference on
Circuits and Systems
Chicago, Illinois
April 1981

Nian-Chyi Huang, Sunghan Park and J.K. Aggarwal, "One Dimensional Linear Time-Varying Digital Filtering Using Two-Dimensional Techniques."

Nian-Chyi Huang and J.K. Aggarwal, "Synthesis of Recursive Linear Shift-Variant Digital Filters."

ACS National Meeting
Atlanta, Georgia
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B.E. Koel and J.M. White, "X-Ray Excited Auger Electron Spectroscopy of Ethylene and Acetylene on Ni(100)."

J.A. Schreifles, S.-K. Shi and J.M. White, "Temperature Dependence of Electron Beam Damage During the Titration of Adsorbed Oxygen with Hydrogen on a Ru(001) Surface."

*Funded entirely or in part by the Joint Services Electronics Program.

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Physics Department
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Bielefeld, Fed. Republic of Germany
April 11, 1981

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Deutsche Gesellschaft fur
Schwerionenforschung
G.M.B.H.
Garmstadt, Fed. Republic of Germany
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L. Frommhold, "Collision-Induced Spectroscopy."

Rice University
Houston, Texas
April 14, 1981

*S.I. Marcus, "Nonlinear Filtering: Pathwise Solution, Finite Dimensional Filters, and Approximations."

IEEE Antennas and Propagation Society
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T. Itoh, "Antenna Research at University of Texas."

Lawrence Berkeley Laboratory
Berkeley, California
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Albuquerque, New Mexico
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B.E. Koel, D.E. Peebles, J.A. Schreifels and J.M. White, "Coadsorption of CO and H_2 on Ni(100) and Ru(001)."

W.M. Daniel, Y.C. Kim, H.C. Peebles, and J.M. White, "Adsorption of Ag, O_2 and N_2O on Ag/Rh (100)."

Solid State Physics Seminar
University of Texas at Austin
May 7, 1981

*R.M. Walser, "Picosecond Laser Damage of Crystal Silicon."

1981 IEEE International Conference on Plasma Science
Santa Fe, New Mexico
May 18-20, 1981

G.A. Hallock, R.L. Hickok, W.C. Jennings, E.B. Hooper, Jr., E.J. Powers, Y.C. Kim and J.Y. Hong, "Low Frequency Fluctuation Measurements in the Central Cell of TMX."

Y.C. Kim, T.P. Kochanski, L. Khadra, R.F. Gandy, E.J. Powers and R.D. Bengtson, "Characteristics of Low Frequency MHD Oscillations in the PRETEXT."

EXXON
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May 20, 1981

J.M. White, "Photoassisted Reactions."

ONR Conference
Renssalaer Polytechnic Institute
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May 21, 1981

J.M. White, "Photoassisted Reactions."

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The University of Marburg-Colloquium
Marburg, Germany
May 22, 1981

M. Fink, "Potentials and Limitations of High Precision Scattering Data."

Massachusetts Institute of Technology
Cambridge, MA.
May 28, 1981

*S.I. Marcus, "Nonlinear Filtering: Pathwise Solution, Finite Dimensional Filters and Approximations."

IEEE International
Microwave Symposium
Los Angeles, California
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P. Yen, J.A. Paul and T. Itoh, "Millimeter Wave Planar Slot Antennas with Dielectric Feeds."

T. Itoh, "Open Guided Wave Structures for Millimeter-Wave Circuits."

*Y. Shih, J. Rivera and T. Itoh, "Millimeter Wave Planar Slot Antennas with Dielectric Feeds."

I. Awai and T. Itoh, "Coupled-Mode Theory Analysis of Distributed Nonreciprocal Devices."

1981 National Radio Science Meeting
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*J.Y. Hong, Y.C. Kim and E.J. Powers, "Modelling of Nonlinear Scatterers with Nonlinear Radar Cross Sections."

D.C. Chang and T. Itoh, "Guiding Mechanisms on Open, Planar Structures."

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J. Rivera and T. Itoh, "Suspended and Inverted Microstrips for Millimeter-Wave Applications."

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Bozeman, Montana
June 19, 1981

J.M. White, "Coadsorbed CO and H_2 on Ni(100)."

Joint ASME/ASCE Bioengineering,
Fluids Engineering and
Applied Mechanics Conference
Boulder, Colorado
June 22-24, 1981

Y.C. Kim, E.J. Powers, F.L. Jones and R.W. Miksad, "Digital Bispectral Analysis of Nonlinear Wave Couplings in Fluids."

Workshop/Conference on
Heterogeneous Catalysis
SUNY
Albany, N.Y.
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J.M. White, "Photoassisted Reactions on Doped Metal Oxide Particles."

Electrical Engineering Seminar
University of California-Irvine
Irvine, California
July 2, 1981

*T. Itoh, "Open Guided Wave Structures for Millimeter-Wave Circuits."

Dow
Freeport, Texas
July 21, 1981

J.M. White, "Photoassisted Reactions."

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Hughes Aircraft Company
Electron Dynamics Division
Project Meeting
Torrance, California
July 23, 1981

*T. Itoh, "Distributed Nonreciprocal Structures."

Seventh International Joint Conference on Artificial Intelligence
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August 1981

J.K. Aggarwal and Jon Webb, "Structure from Motion of Rigid and Jointed Objects."

URSI General Assembly
Washington, D.C.
August 1981

*T. Itoh, "Planar Dielectric Waveguides and Other Surface-Wave Structures."

IEEE Pattern Recognition Image Processing Conference
Dallas, Texas
August 1981

J.K. Aggarwal and Sudhakar Yalamanchili, "Motion and Image Differencing."

J.K. Aggarwal and W.N. Martin, "Occluding Contours in Dynamic Scenes."

Advanced Flight Control Symposium
Air Force Academy
Colorado
August 4, 1981

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XXth General Assembly of URSI
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August 10-19, 1981

J.M. Beall, Y.C. Kim and E.J. Powers, "Experimental Estimation of Spectral Densities of Plasma Wave Turbulence."

NASA/DoD Meeting on
Near Millimeter Waves
and Their Applications
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I. INFORMATION ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE81-1 NONLINEAR DETECTION AND ESTIMATION

Principal Investigators: Professor S.I. Marcus (471-3265)
Professor J.L. Speyer (471-1356)

Graduate Students: Jessy Grizzle, Chang-Huan Liu and John White

A. OBJECTIVES AND PROGRESS: This research unit is concerned with several aspects of the statistical properties of nonlinear systems. Specifically, the design and analysis of optimal and suboptimal nonlinear estimators, the modeling of nonlinear systems driven by general noise processes, and the problem of detecting and identifying failure modes in fault tolerant systems have been investigated.

1. Nonlinear Estimation:

The area of nonlinear state estimation is concerned with the extraction of information about the state of a stochastic system from nonlinear noisy measurements. The state estimate is generated by passing the measurements through a nonlinear system. Optimal state estimators have been derived for very general classes of nonlinear systems, but these are in general infinite dimensional. That is, it is usually not possible to recursively generate the optimal minimum variance estimate (the conditional mean) of the system state given the past observations. The basic objective here is the design, analysis, and implementation of high-performance optimal and suboptimal estimators which operate recursively in real time. There are few known cases aside from the linear (Kalman) filtering problem in which the conditional mean (the minimum variance estimate) of the system state given the past observations can be computed recursively in real time with a filter of fixed finite dimension. However, in [1] we have proved that for certain classes of discrete-time and continuous-time systems, described either by a finite Volterra series or by certain types of state-affine realizations, the minimum variance estimator is recursive and of fixed finite dimension. This was accomplished by relating these problems to the homogeneous chaos of Wiener and to orthogonal expansions of Gaussian processes.

Benes [2] has recently given an explicit solution for the conditional density for a class of nonlinear filtering problems with nonlinear state equations and linear observations. In [3] we have extended his results and our results of [1] in the following way. In [1] we found finite dimensional filters for the conditional moments for problems involving linear systems feeding forward into nonlinear systems; in [3], we have studied problems in which systems of Benes type feed forward into nonlinear systems of the type considered in [1]. We have derived recursive filtering equations for the conditional moments of Benes problem and used these to derive new finite dimensional optimal filters for the class of nonlinear systems described above.

In a Lie algebraic approach to nonlinear filtering, we have studied the (Zakai) stochastic partial differential equation for an unnormalized conditional density $\rho(t,x)$ of the state x_t given the past observations $\{z_s, 0 \leq s \leq t\}$:

$$d\rho(t,x) = L_0\rho(t,x)dt + L_1\rho(t,x)dz_t \tag{1}$$

where L_0 and L_1 are certain differential operators. The major idea of the approach is that, if L is the lie algebra generated by $L_0 - \frac{1}{2} L_1{}^2$ and L_1, and if a recursive finite dimensional estimator for some statistic of the state exists, then there should be a Lie algebra homomorphism from L to the Lie algebra F of the finite dimensional filter. F is a Lie algebra of vector fields on a finite dimensional manifold, so the representability of L or quotients of L by vector fields on a finite dimensional manifold is closely related to the existence of finite dimensional recursive filters.

The structure and representability properties of L are analyzed for several interesting classes of problems in [4]. It is shown that, for certain nonlinear filtering problems, L is given by the Weyl algebra $W_n = \mathbb{R}\langle x_1,\ldots,x_n, \frac{\partial}{\partial x_1},\ldots,\frac{\partial}{\partial x_n}\rangle$ of all polynomial differential operators. These problems include the cubic sensor problem (linear system with cubic observations) and some examples of mixed linear-bilinear type. It is proved that neither W_n nor any quotient of W_n can be realized with C^∞ or analytic vector fields on a finite dimensional manifold, thus suggesting that for these problems, no statistic of the conditional density can be computed with a finite dimensional recursive filter. This work, together with some results of Sussmann, implies that for some problems (including the cubic sensor), no nontrivial statistics can be computed recursively with finite dimensional filters; this is the first such result in the literature. For another class of problems, it is shown that L is a certain type of filtered Lie algebra. The algebras of this class are of a type which suggests that many statistics are exactly computable.

In [5], we have studied the modeling and approximation of stochastic differential equations driven by semimartingale noise containing both continuous and jump components. We have defined for the first time the analog of the Stratonovich differential equations when the noise has both jump and continuous components. It is proved that the models defined here possess a number of approximation and continuity properties. The importance of this work is related to the fact that, for models to be faithful representations of physical systems, the system variables should not be affected significantly by small changes in the noise processes driving the system. The results presented show that our models are, under certain hypotheses, consistent in this sense.

The work of [5] is used in conjunction with Lie algebraic methods in [6] and [7] to find low dimensional filters for a class of estimation problems with Poisson observations. In this problem, a finite state Markov process x taking values in $S = \{s_1, \ldots, s_n\}$ is the rate of an observed doubly stochastic Poisson process z, and it is desired to recursively estimate the rate x_t. This can be accomplished with an n-dimensional recursive nonlinear filter derived by Segall and Van Schuppen. However, there are two problems: this filter is highly nonlinear, and its dimension may be very large. In [6] and [7] we eliminate the first objection by deriving a bilinear equation for an unnormalized conditional probability vector. We then study the Lie algebraic structure of this bilinear filter and find a class of problems for which the conditional probability vector (and hence the conditional mean) can be computed with a <u>two-dimensional</u> filter, for <u>any</u> n. This is, of course, a considerable computational saving if n is large.

The negative results of [4] are interesting, but it is much more useful to design high-performance suboptimal estimators for systems which have no exact finite dimensional filters for conditional statistics. In [8] estimation problems for systems involving small parameters have been studied via both analytical and Lie algebraic approximation techniques. The typical system considered is of the form

$$
\begin{aligned}
dx_t &= ax_t dt + dw_t \\
dz_t^{\varepsilon} &= [x_t + \varepsilon (x_t)^k] dt + dv_t \quad , \quad k \geq 1
\end{aligned}
\tag{2}
$$

-- i.e., it is a "weak polynomial sensor" problem. We have first expanded the unnormalized conditional density $\rho(t,x)$ satisfying (1) powers of ε

$$\rho^{\varepsilon}(t,x) = \rho_0(t,x) + \varepsilon\rho_1(t,x) + \varepsilon^2\rho_2(t,x) + \ldots \tag{3}$$

and have for the first time showed that

$$\rho^{\varepsilon}(t,x) - \sum_{i=0}^{n} \varepsilon^i \rho_i(t,x)$$

is actually $O(\varepsilon^{n+1})$ in a suitable norm; i.e., (3) is a true asymptotic expansion. In addition, we have shown similar results for the normalized conditional density and conditional mean.

Even if (3) is an asymptotic expansion, it is not of much use in nonlinear estimation unless each term in (3) can be computed with a finite dimensional recursive filter. This is shown in [8] by Lie algebraic techniques. By substituting the expansion (3) into (1) and truncating after n terms, we obtain a set of coupled stochastic partial differential equations; however, each equation is coupled only to lower order, not higher order equations. In addition, the Lie algebra of these equations up to order n is solvable and finite dimensional; hence the equations can be solved by the Wei-Norman method. This method results in a recursive finite dimensional filter for a set of sufficient statistics, from which the expansions of the conditional density and conditional mean can be computed by a memoryless operation.

The research in this area is continuing and has been complemented by Grant AFOSR-79-0025 from the Air Force Office of Scientific Research and Grant ECS-8022033 from the National Science Foundation.

2. <u>Fault Detection and Identification:</u>

An essential aspect in the design of fault tolerant digital flight control systems is the design of fault detection systems. Design considerations are concerned with the trade-off between the cost of hardware redundance and the complexity and robustness of the software for analytic redundancy. In analytic redundancy dissimilar instruments are combined through analytic relations to achieve redundancy. Since these relations contain system parameters, additional uncertainty may be introduced beyond that present in the sensors. The processing of the outputs of these relations to produce adequate fault detection and isolation performances may require complex decision and estimation software. In [12], we have developed a particular decision rule which seems simple to implement on flight computers, yet sensitive enough to produce adequate performance. This decision rule, based upon the results of Shiryayev [9] and suggested to us by Deyst [10], has application to fault detection for both similar instruments and dissimilar instruments through analytic redundancy.

Given a sequence of independent measurements, the Shiryayev sequential probability ratio test (SSPRT) will detect a disruption (or fault) in the data sequence in minimum time with certain conditions. This (SPRT) differs from the Wald SPRT since there is no need to mechanize a "trigger" [11]. In fact, the SSPRT can be reduced to the Wald SPRT when the probability of change in state (the transition probability) is made zero. One objective is to investigate the robustness of the SSPRT in that we require that it be a continuous fault monitor. Attention is given to its response time in detecting a fault and to the frequency of false alarms.

The likelihood ratio of the SSPRT is derived explicitly in [12]. We assume that the measurements are independent and of known probability densities (the fault bias is known), and the transition probability, the a priori probability and the threshold values are given. For a scalar data sequence and two hypotheses (the measurement sequences are governed by either of two probability laws), a scalar linear difference equation with state dependent noise is propagated. The multiplicative noise term is composed of the ratio of the probability laws, which is a function of the present measurement. A dynamic programming analysis shows the optimality of the SSPRT. In [9], Shiryayev shows that a cost function composed of the probability of false alarm summed with the cost of average delay of detecting the occurrance of the disruption is directly related to the optimal stopping problem with a given threshold. In [12], the threshold for the likelihood ratio has been chosen as a given ratio of the probability that the fault has occurred in the data sequence to the probability that it has not. This threshold can be related to the cost of false alarms by the dynamic programming analysis.

Although the Wald SPRT used in [11] requires the uncertainty in the data sequence to be Gaussian, the probabilistic description can be quite general for the SSPRT. This generality is used to advantage in our results for the case where the sign of the bias is unknown. Since the Wald SPRT depends explicitly on the sign of the bias, two Wald SPRT's are propagated in [11]. However, the absolute value of the data sequence, which is non-Gaussian, even if the original data sequence is Gaussian, can be processed in the SSPRT. The resulting SSPRT is not increased in complexity. On the contrary, whereas an exponential function of the data had to be calculated, a cosh function of the data is calculated at each sample point. The cosh function, being an even function, can be calculated numerically more efficiently.

To gain insight into the performance of this test, two problems are chosen in [12]. Since the sequential tests are more efficient in detecting a fault than fixed interval schemes such as sliding window averages and consistency tests, the SSPRT is used in direct redundancy tests between two like instruments. Here, two rate gyros are modeled and the SSPRT is applied. Performance is compared with the standard tests with regard to detection time and false alarm rate. Furthermore, the mechanization of the SSPRT with regard to processing time and computational complexity is compared with that of standard tests.

The second experiment is to form a parity relation among various instruments. The particular test chosen is the translational kinematic redundancy test described in [11]. One objective is to show how the SSPRT can be used to detect accelerometer or rate gyro failures without a redundancy trigger, i.e., only one instrument is necessary. This circumstance occurs when the instruments are very expensive. This test was chosen since some results are already reported [11].

In [11], an open loop dynamic comparison test is developed. In this test, the measured acceleration is integrated and compared with the difference between the initial measured velocity and the present measured velocity. The effect of this test is to improve the signal-to-noise ratio since the design bias is increasing with time and the dominant noise variance associated with the measured velocity, although large, remains fixed. However, since no trigger is available for the SSPRT, this open loop dynamic comparison cannot be used. Rather, the data sequence for the SSPRT is obtained by integrating the measured acceleration over a number of sample times and comparing this velocity with the difference between the measured velocity at the end and the beginning of this interval. In this way, the signal-to-noise ratio is improved at the expense of a reduced data sequence. To improve performance, we suggest using two tests, in which one test will rapidly detect hard over faults, while the other will be adjusted to detect more subtle faults. In the experiments of [12], the data sequence is constructed as described above, using the sensor models for the translational kinematics given in [11]. However, the given variance associated with the angle-of-attach meter was reduced by an order of magnitude. These variances were kept artificially high in [11] so as not to produce false alarms near the beginning of the test. Since we process information at a slower rate, more realistic variances are used. In our study a design bias of .2 g's is used. For an ensemble average of 30 runs, the average detection time was 4.2 sec. using an integration interval of ten times the sample time of .0625 sec. This is compared with 2.2 sec. (one run) of [11] to detect a failure after the trigger was tripped. This study shows the tradeoffs between integration intervals and bias levels with regard to detection times and false alarm frequency. Furthermore, increasing the integration interval has the effect of reducing the influence of wind shear on the detection process when the correlation times are small enough.

The research in this area is continuing and is complemented by a grant from General Dynamics, Fort Worth Division.

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THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE81-2 ELECTRONIC MULTI-DIMENSIONAL SIGNAL PROCESSING

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A. PROGRESS: The basic objective of the research unit is to develop efficient techniques for processing multi-dimensional signals and the analysis, synthesis and implementation of linear time-varying (LTV) digital filters. Linear time-varying digital filters are important in processing signals where frequency content changes significantly with time. The use of LTV digital filters to process nonstationary sequences has received considerable attention in many applications such as geophysics, communication systems, speech analysis and synthesis [1]. Our research has been directed toward the development of new techniques to synthesize and implement LTV digital filters.

We have investigated the interrelationships among three characterizations of LTV digital filters; the impulse response, the generalized transfer function and the time-varying difference equation [1]. Specifically, we have proven that an impulse response is realizable as a recursive time-varying difference equation if and only if it is expressed as a degenerate sequence. In the frequency domain, the short-time spectrum is a useful measure of the frequency content of nonstationary sequences. In [2], [3], we have proposed an efficient technique to determine the generalized frequency function of an LTV digital filter from the short-time Fourier transform of an input sequence. The technique allows spectral modification to vary with the changing frequency content of a desired sequence and the resultant bandwidth of LTV digital filter to be much narrower than that of a linear time-invariant (LTI) digital filter.

Motivated by the above property of the impulse response of a time-varying difference equation, we have developed two synthesis techniques which approximate a given impulse response by a degenerate sequence [4], [5]. Both techniques use a least squares error criterion to minimize the difference between the given and the approximated impulse responses. The first technique is formulated as an approximation of an arbitrary function of two integer variables by sums of separable functions. The filter synthesized by this technique is optimal for the given criterion. However, the implementation of the resultant filters needs to store a large number of filter coefficients. In order to circumvent this difficulty, the degenerate impulse response is represented in terms of simple functions with unknown parameters. These unknown parameters are determined by a nonlinear optimization method which minimizes the distance function. This second technique is more efficient in implementation but may yield suboptimal filters. In addition, several recursive structures for implementing degenerate impulse responses have been investigated.

In [6], we have developed a new technique to implement a one-dimensional (1-D) LTV digital filter with a two-dimensional (2-D) linear time-invariant (LTI) recursive digital filter. By appropriately mapping 1-D input/output sequences into 2-D sequences, 1-D LTV digital filtering may be carried out by a 2-D LTI convolution. In doing so, synthesis techniques developed in LTI digital filters have been applied. The use of this technique has eliminated certain difficulties encountered in implementing LTV digital filters such as the storage of a large number of filter coefficients and the updating of LTV recursive filter coefficients at each sampling instant, but at the expense of more computation time.

A conventional time-domain technique to characterize an optimal filter is based on the least mean squares (LMS) error criterion. In general, it requires a large amount of computation time to obtain the impulse response. We have compared the filter performance and the computation requirements of the time- and frequency-domain techniques based on the mean-squared difference between the actual and desired output sequences when a nonstationary input sequence contains Gaussian noise [7]. Our result demonstrates that the frequency-domain technique is efficient but yields suboptimal filters.

As it has been reported earlier, significant progress has been made in the stabilization and synthesis of 2-D semicausal recursive filters. However, the use of semicausal filters requires a large amount of extra grid points to process a 2-D image. In [8], we presented a method to reduce the size of the output frame. This is done by augmenting the input image with the state-control signal; this prohibits propagation of the state vector beyond the prescribed frame. Our implementation technique provides a desirable means to get an output image without computing the states outside the prescribed rectangular

We plan to continue the present research efforts on problems associated with the synthesis and implementation of LTV digital filters and multi-dimensional signal processing.

In one of our current research programs, we are pursuing methods to realize a generalized transfer function as an LTV recursive difference equation. The synthesis of LTV digital filters has been difficult due to the absence of a correspondence between the coefficients in a time-varying difference equation and the generalized transfer function. With this observation, we propose to develop synthesis techniques which minimize the mean squared error between the impulse responses of a given generalized transfer function and the synthesized LTV recursive difference equation. The determination of filter coefficients in this technique may require large storage and computation time, especially in the case of filtering an input sequence with long duration. Therefore, it is desirable to consider an approximate technique which may yield locally optimal filters which are more efficient in computation. In another project, we are considering the efficient synthesis and implementation of multi-dimensional filters.

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II. SOLID STATE ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE81-1 INTERFACE REACTIONS, INSTABILITIES AND TRANSPORT

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A. RESEARCH OBJECTIVES: The overall objective of this research is to expand on our understanding of fundamental processes at the interfaces of electronic structures. The interface structures of interest are contacts and or barriers whose stability determines the overall lifetime and reliability of electronic devices and circuits. The fundamental information gained in these studies is also expected to be potentially useful for synthesizing new and improved electronic devices and materials.

In our previous research we have shown that electronic instabilities may drive the solid phase surface chemical modifications that alter the properties of electronic interface structures. Many surface chemical kinetic paths are available for relieving the instabilities, but the actual path selected may depend upon a large number of experimental parameters and selective chemical kinetic paths cannot generally be predicted. At present our work is being concentrated on (1) understanding the fundamental, and possibly universal origin of the electronic instabilities and (2) experimentally exploring their relaxation in specific important electronic systems.

In the past year our research has been focused on two general problem areas. The first area concerns the general problem of understanding the reaction paths selected by silicon interfaces at low reaction temperatures, i.e., below eutectic and melting points in the equivalent bulk systems. We are particularly interested in the reaction paths for transition metal-silicon interfaces. Progress in several related studies of these systems are reported in the next section. In the past year we have concentrated on measurements of excess "$\frac{1}{f}$" noise in Co-Si films through the first nucleation regime as well as a determination of the reaction path in Cr-Si and Ti-Si systems.

The second area of concentration is the study of laser-induced surface instabilities in solids which has the specific objective of investigating the physics of non-equilibrium nucleation phenomena in solids. In the past year we have been studying the laser damage of crystalline silicon by intense, multiple, large beam area pulses from the perspective of non-equilibrium phase transitions. To do so we developed new experimental techniques for demonstrating that the iso-intensity damage transformation kinetics in the vicinity of the damage threshold intensity exhibited the features of a classical nucleation and growth. Although the statistical nature of the damaging interaction of light and matter had previously been observed for large area, single pulse damage of transparent media, ours was the first reported study of the evolution of damage by multiple pulses of variable, but near threshold intensities. The results of this work will be described more fully in the next section.

B. PROGRESS:
Research on First Silicide Reaction Paths

We have prepared and measured many Co-Si samples both "as sputtered" and after gentle annealing at 200°C. In particular, we have monitored resistance and the excess noise characteristics. Although our initial measurements have indicated significant scatter in the data vs. sputter deposition time, significant trends have been noted as indicated in Figures 1 and 2. In Figure 1, we have plotted the magnitude of the noise vs. the sample resistance. (Note that in these films the semiconductor-metal and noncrystalline-crystalline transitions have been shown to occur at about 10^4 Ω/□ [1]. In Figure 2, we plot the frequency exponent β (noise power $\propto \frac{1}{f^\beta}$) vs. film resistance. We see that both plots indicate anomalous "$\frac{1}{f}$" noise as the films approach and go through the first nucleation regime. In terms of models of Ngai, et al [2] and Hill, et al [3] these results indicate significant systematics in the metastable coherent state correlation parameter m (or n).

Both the Cr-Si and Ti-Si thin film systems have been investigated by TED, and resistance in the regime leading to nucleation: critical thicknesses and annealing temperatures for silicide formation have been established in both systems. In the Ti-Si system it was found that a non-equilibrium compound phase was formed prior to $TiSi_2$ nucleation. However, the transmission electron diffraction results indicate that this phase (labeled "TiSi" by previous researchers) is not the TiSi phase in the equilibrium phase diagram. This finding is significant for the systematics of the overall selection rule for first nucleation. In addition , the Ti-Si system is important as an end phase region in work recently started on the ternary systems Ti-Ni-Si and Ti-Co-Si. Initial measurements on these ultrathin film systems indicate we may significantly affect the final product formed by thickness and order of sequential deposits of the two transition metals on Si substrates. These findings may be quite important in the refractory metal silicide interconnect and gate areas for VSLI technology as well as give new insights into the first nucleation sequence in the solid state regime.

Studies of Picosecond Laser Damage In Crystalline Silicon

In this research we have conducted detailed experimental studies of picosecond laser induced damage as a non-equilibrium phase transition and proposed a new damage mechanism. This model which includes energy transfer by resonant surface plasmons on small electron density droplets is corroborated by our existing experimental data. New experimental data has been taken which demonstrates the nucleation and growth aspects of the laser damage process [4,5].

The motivation for this work has its origin in several facts. First, the picosecond time domain results in several simplifications due to the elimination of transport during the pulse duration. Near band-gap excitation at 1.06μm limits the heating of the sample by fast phonon decay of hot electrons. Silicon, a covalent material, was chosen for the absence of polar optical coupling mechanisms and the absence of an electron collision time sufficiently short to allow avalanche ionization. Finally, experience gained in the excitation of VO_2 through a non-equilibrium phase transition in the first such study [6] led to a conceptual framework for these types of experiments.

We have performed an experimental demonstration of the heterogeneous nature of the nucleation and growth of laser damage in crystalline silicon. The samples of single crystal silicon were prepared from low resistivity <100> and <111> wafers with high resistivity 1.5 or 2.5μm epitaxial layers. To obtain the very thin samples used in some experiments, the wafers were masked and electrochemically etched, exposing about $0.5cm^2$ of epitaxial membrane [7].

The damage nucleation and growth was studied by monitoring the transmission of the irradiated region at 633nm while multiple pulse damage was initiated at a prf of 5Hz. The laser pulses were supplied by a passively modelocked 1.06μm Nd:YAG laser. Single pulses were selected with an average FWHM duration of 38psec.

The sample transmission could then be related to a percent of the spot area transformed to the final state of damage. The results of this measurement showed an incubation period, a sigmoidal shape and have been fit to the Avrami equation for the behavior of nucleation and growth. These results strongly suggested that this damage process is a heterogeneously nucleated first order phase transformation process. This in turn suggested that a morphological study of the nucleation process would be beneficial.

A systematic study of the morphology of laser damage of silicon has been conducted. The multiple pulse damage threshold represents the point of closest approach to the phase transition where the morphology of nucleation may be studied. This method avoids the catastrophic damage characteristic of single pulse damage which would tend to destroy evidence of its early formation stages.

An automatic translation stage was constructed for the sample which would count laser pulses and give a sequence of irradiations at increasing powers of two pulses.

A high resolution SEM study showed the development of the coherent damage morphology with increasing numbers of pulses. The nucleation of the damage appears first as oval pits with their long axis orthogonal to the optical field. Subsequently and simultaneously formed pits are regularly spaced along single rows. Parallel rows of pits finally form into grating structure. Clearly the first phase of the damage process self-consistently selects pit formation at a specified distance from another pit, orthogonal to the optical field. The second phase of damage is the formation of regular spaced rows of pits (grooves). The grooves are spaced by the free space wavelength, suggesting that they are formed by the constructive interference of a scattered surface wave and the incident wave. This second process is consistent with the damage observed to propagate from preexisting linear structures such as scratches oriented normal to the optical field.

All of the damage we observed in these experiments was at the front surface. Even the optically thin 1.5μm thick films damaged first at the front surface. Near threshold, only front surface damage was observed. Since our silicon samples were extremely thin compared to the absorption length, this observation indicates that the damage could not have been initiated by the optical electric field, which by simple Fresnel arguments, is a maximum on the exit surface.

Silicon, with a band gap of 1.1ev at 300K, has a linear absorption constant of only $10cm^{-1}$ for 1.06μm laser pulses. At intensities approaching the multi-pulse damage threshold, our experimentally measured transmission data indicates the presence of an additional two photon absorption. Assuming that an indirect two photon process dominates, we obtained a two photon absorption constant β=52cm/GW by fitting the data.

Using this absorption process for 38 psec 1.06μm pulses at an intensity of $1GW/cm^2$ only 10^{18} to 10^{19} charge pairs are produced per cm^3. In addition, the computed temperature rise during the pulse is less than one degree K. Although free carrier absorption was omitted from these calculations, it is not expected to increase the refractive index or temperature jump significantly.

These extrapolated values of ΔT and Δn are much too small to initiate catastrophic damage which is, of course, the basic scientific enigma found in nearly all studies of laser damage in nearly-transparent media. Note that electronic avalanche ionization is not a highly probable process at the high excitation frequency of the Nd:YAG laser and, is ruled out by our observation of entrance face damage in thin samples.

To circumvent these difficulties we have proposed a new laser damage mechanism suggested by the morphological studies of the early damage nucleation regime [8,9]. This work suggests that, despite the apparent absence of avalanching, locally high absorption in some highly excited, small, charge density "embryos" is the precursor to damage. Furthermore, the consistent observation of coherently interfering "embryos" indicates that these are of <u>intrinsic</u> origin and not due to the presence of highly absorbing extrinsic heterogeneities.

We are led to suggest that an electronic spinodal separation occurs near the threshold when the average excited charge density approaches $\sim 10^{19}/cm^3$. Inside the spinodal the electron and hole excitations are subject to spontaneous clustering under the influence of some unknown driving force.

The proposed damage mechanism involves the resonant absorption of incident photons by the collective electronic oscillations (surface plasmons) of embryo regions having near-critical radii and excited charge density approaching that of the liquid. This model is consistent with the evidence of cooperative interaction between damage sites. The direction and separation of the sites are those expected of a coherent radiative interaction between resonant surface plasmons on adjacent sites just prior to liquid phase nucleation.

While normally incident light will not couple to the planar surface plasmons of a solid, it will couple efficiently to any charge density droplets that form. The coupling will be resonant for a droplet size and charge density such that $\omega_{sp}=\omega_o$. Damage will nucleate at the lowest intensity for which coherent radiative coupling occurs between the resonant surface plasmons of two or more droplets.

A small, compared to lambda, spherical charge droplet will support a number of surface plasmon modes. Our calculations show that the lowest mode will be resonant in energy with the laser photons at a density of $n = 2\times10^{22}$ cm^{-3}. From the classical theory of radiating dipoles, we have computed the in phase and quadrature components of the radiated field in a direction orthogonal to the optical field. The minimum spacing for which the radiative fields will constructively interfere is at a separation of $1.2\lambda_{Si}$ or about 375nm. (A value of 3.4 was used for the refractive index of silicon). This interaction distance compares favorably with the 350-380nm values obtained from our SEM experiments.

The proposed mechanism should result in a large increase in the laser energy deposited micro-heterogeneously at the surface near the damage threshold. It is not clear, however, how the material will relax such an intense, fast, local electronic excitation. As discussed in the following section we are continuing our research in this area in an attempt to resolve this question and to further assess the validity of our laser damage model.

C. FOLLOW UP STATEMENT: Both the excess noise measurements and the ultra thin film ternary work are being continued. The excess noise is being measured on similar systems as in the past in an effort to determine the source of some of the scatter in the measurements and to reduce it. The measurements will probably be extended to the Ni-Si system to begin to determine the generality of the observed systematics. Also, we will begin the comparison of our measurements to recent models of excess noise to determine their applicability with a view toward modifying and extending these models.

The Ti-Co-Si and Ti-Ni-Si ternary ultra thin film work is being continued predominantly in the area of increasing the number of measurement combinations in terms of different thicknesses and annealing conditions. In the next year we will be making a significant effort at determining the systematics of reactions in ternary systems. This will probably primarily be involved with modelling the constituent supply problem which is midway between the two extremes of preselection and kinetic selection as is observed in binary thin film systems.

We are continuing our studies of laser induced damage in crystalline silicon and have begun to do similar exploratory studies of various other semiconductors (including amorphous silicon) and metals.

Since completing our initial multiple pulse damage studies on crystalline silicon we have acquired a microcomputer controlled system for monitoring and recording the intensity of each picosecond pulse. This system will greatly enhance our ability to explore the intrinsic statistics of the laser damage physics while minimizing the role of the statistical fluctuations of the laser.

We have also recently discovered that the large beam single shot threshold intensity of silicon samples is more sensitive to surface preparation conditions than previously believed. This is encouraging for the model of the laser damage statistics that we are developing which predicts a considerably larger difference in the single and multiple pulse threshold intensities than those observed previously.

In the past year we have also made some initial measurements of the intensity variation of exo-emission currents from the surface of a material in the vicinity of the laser damage threshold. Initial experiments with silicon indicate that the energetic processes responsible for exo-emission near the single and multiple pulse thresholds are very different. We will continue these exo-emission experiments and correlate the results with the morphological development of damage in order to further clarify the nature of the critical energy transfer processes leading to damage.

Finally, we expect to extend these studies to other semiconductors and to some metals. Our first experimental observations indicate that the multiple pulse damage morphologies produced by picosecond YAG pulses on GaAs and some metals (nickel and aluminum) are surprisingly similar to those observed in silicon. It is not clear, however, that a model like that developed for silicon will apply to these other materials.

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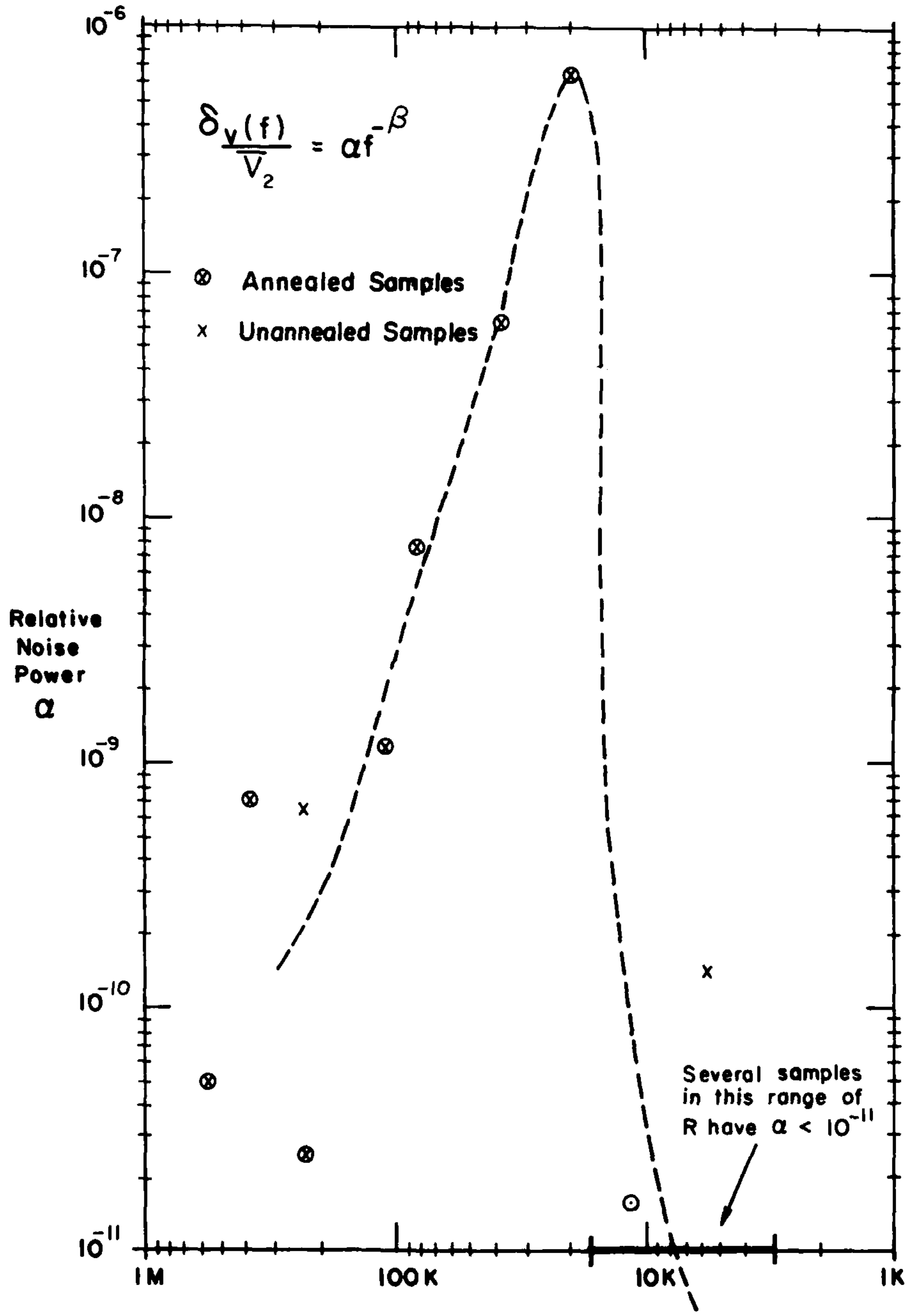

Figure 1. Relative Noise Power vs. Resistance

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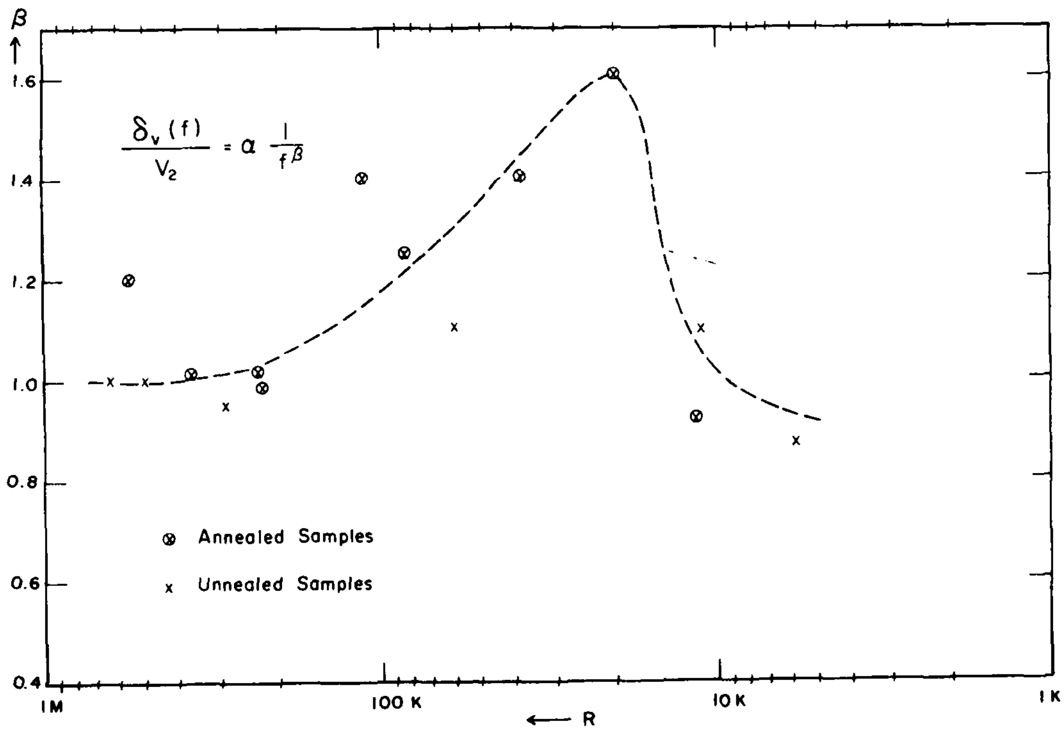

Figure 2. Frequency Exponent vs. Resistance

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
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Research Unit SSE81-2 SPECTROSCOPIC STUDIES OF METAL/SEMICONDUCTOR AND METAL/METAL OXIDE INTERFACES

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A. OBJECTIVES: The scientific objective of this research unit is to investigate atomic and molecular level properties associated with selected solid surfaces and solid state interfaces. The work is divided into three related subareas: 1) metal/semiconductor interfaces, 2) metal and semiconductor surface/adsorbate systems, 3) metal/metal and metal/metal oxide systems.

Research on metal/semiconductor interfaces is focused on understanding the electronic structure and composition of silicide structures which form when metal atoms deposited on a semiconductor surface react to form an interface. Particular emphasis is being directed towards understanding the initial stages of interface formation. This work utilizes Auger electron spectroscopy (AES), to characterize near surface composition, low energy electron diffraction (LEED) to determine geometrical structure, angle resolved photoelectron emission spectroscopy (ARPS) to study electronic properties of the constituent atoms, and x-ray photoelectron spectroscopy (XPS) to study the chemical state of silicon and the deposited metal. Additional effort is being directed towards developing a nondestructive means of probing the electronic structure in practical interfaces. This work will utilize optical reflectance to obtain the multilayer dielectric constant associated with a practical interface. The dielectric constant when correlated with results of other experimental techniques such as AES and channeling, should give a reasonably good picture of the electronic structure and composition of practical metal/semiconductor interfaces. Depth-profiling with AES and XPS analysis of these systems will also be employed.

Research on surface/adsorbate systems is primarily oriented towards supporting our work on metal/semiconductor interfaces and on metal/metal oxide interfaces. In preparing any solid state interface, impurity atoms and molecules are incorporated from the background of atomic and molecular species in the vacuum chamber. These impurities can chemisorb at surfaces where interfaces are being formed and can influence the growth kinetics, electronic properties, and crystal structure of the interface. Our research includes investigations of the structure and composition of selected adsorbates on semiconductor, metal and metal oxide surfaces with emphasis on materials used in interface systems being investigated under metal/semiconductor and metal/metal oxide headings. Several state-of-the-art experimental techniques are available to accomplish this work. These include the capability to obtain the vibrational spectra of atoms and molecules at surfaces using high resolution electron energy loss spectroscopy (EELS). These capabilities provide an opportunity to obtain detailed structural information related to species adsorbed at solid surfaces.

Research on metal/metal oxide interfaces is focused on the development of depth profiling and analysis methods of studying the top most atomic layers that form when a clean metal is exposed to oxygen. This work will utilize electron spectroscopy, particularly XPS, to obtain substrate core level intensities. Of great interest are satellite intensities of core levels which reflect changes in the metal/ metal oxide interactions.

In a related materials area, the fundamental problem of how one metal binds to another is being studied. The techniques include LEED, AES and flash desorption spectroscopy (FDS). From these measurements metal-metal binding energies, ordered metal overlayer structures and electronic structures of metal-metal overlayer systems are being investigated. Such information is crucial in understanding alloying and segregation. From FDS, quantitative values for the heat of desorption can be measured as a function of coverage. LEED provides data on the development of ordered overlayers and AES, when analyzed in detail, provides local chemical bonding information in addition to atomic composition.

B. PROGRESS: We have made significant progress in several subareas indicated in section A which summarizes our objectives. This section outlines scientific progress in these subareas and describes additional efforts to improve the instrumentation required for our research.

1. Metal Semiconductor Interfaces

Our proposed work on transition metal silicide interface formation utilizes Auger electron spectroscopy (AES), low energy electron diffraction (LEED), ultraviolet photoelectron emission spectroscopy, (UPS) and optical reflectance. One spectrometer being used for this work is now complete, and a second spectrometer which will be used at the synchrotron radiation center in Stoughton, Wisconsin is nearing completion. Work on the reflectance spectrometer has been discontinued temporarily due to space limitation.

a. Bulk Silicide Electronic Structure

We have successfully conducted the first detailed experimental study of the bulk electronic structure of an ordered silicide [1]. Structural and electronic properties of expitaxial $NiSi_2$ crystals were investigated using LEED, Auger spectroscopy and angle resolved photoelectron emission. Our $NiSi_2$ samples were prepared in situ by vacuum evaporating Ni onto Si crystal surfaces. Excellent epitaxial crystals can be formed on Si(111) and Si(100) surfaces as verified by our own LEED studies and by ion channeling [2].

Normal emission UPS spectra from (111) and (100) $NiSi_2$ surfaces yielded band dispersions and critical point binding energies along Γ-L and Γ-X directions of the bulk Brillouin zone. Our experimental results are in good agreement with recent self consistent energy band calculations [3]. Our LEED, Auger and workfunction results suggest that (100) and (111) $NiSi_2$ crystals grown epitaxially terminate in a silicon layer and nickel layer, respectively.

b. Initial Stage of Silicide Interface Growth

Preliminary results have been obtained for initial growth of silicides at silicon surfaces [4]. We have studied the evolution of the nickel d-band structure and surface work function changes as a function of the thickness of nickel deposited onto silicon surfaces. These studies have been made for several surface reaction temperatures. Our results suggest that the room temperature interface depth is less than 10Å for nickel evaporated onto silicon. Our results also indicate that it is relatively easy to distinguish between the three stoichiometries (Ni_2Si, NiSi and $NiSi_2$) which can form when nickel is reacted with silicon to form an interface.

c. New Instrumentation

We are continuing to upgrade our research capabilities by improving existing equipment and constructing new instruments. Our split beam reflectometer remains in the development stage. We currently lack adequate floor space to put this spectrometer into operation, and also will require some minor instrumentation (a sputter gun for cleaning samples) before the instrument will be useful for research. Our major instrumentation effort this year has been to construct a new angle resolving photoelectron spectrometer [5] which will be used at the synchrotron radiation center in Stoughton, Wisconsin. This new spectrometer will introduce several unique new capabilities to our laboratory which will benefit our JSEP sponsored work.

2. Surface Adsorbate System

Our high resolution electron energy loss spectrometer (EELS) is now operational with LEED and Auger spectroscopy capability. Research using this instrument is being sponsored by AFOSR. We have recently obtained some important new results regarding the oxidation of Al(111) using EELS [6]. We have shown that the initial stage of oxidation of Al (111) is characterized by a mixed phase consisting of both surface and subsurface atomic oxygen. The surface phase is unstable and converts to subsurface oxygen at room temperature. No evidence of molecular oxygen was observed in our experiments contrary to other work. Our EELS study also illustrates a new application of the technique: the study of underlayer structures, and in addition shows that the "dipole" scattering mechanism applies to subsurface dipoles at metal surfaces.

3. Non Reactive Metal/Silicon Interfaces

In separate experiments, we are constructing in the Chemistry Department an instrument for investigating the behavior of submonolayer to multilayer amounts of Ag on Si (111). The instrument is designed for LEED, AES and TPD measurements and employs a thermal evaporation source for controlled Ag deposition. This system is an important part of our overall silicide program because silicides of Ag do not form readily, if at all. This provides a good benchmark system for studying chemisorbed metal atom overlayers without surface compound formation. At this time, the system is completed with the exception of an external gas handling system and minor modifications of the crystal mount to provide better TPD spectra.

4. Metal/Metal Oxide and Metal/Metal Systems

As part of our program on the behavior of oxide layers on metals, we have just completed a study of electron beam damage due to oxygen ion desorption, on oxided ruthenium surfaces [7].

The reaction is characterized by three kinetic regions when Ru(001) is exposed to 100 L of O_2 at 865K and then titrated with H_2 at this or lower temperatures. The first region is a long induction period, the second a rapid reaction region and the third a slow reaction region. The first two of these are sensitive to electron beam effects, i.e., the 3-5 kV and 5-20μA beam used for Auger analysis. In particular, the induction time is dramatically shortened (by as much as a factor of 10) when Auger analysis with a focussed e-beam is used. We use x-ray photoelectron spectroscopy as a standard which eliminates e-beam damage. This effect is temperature sensitive and disappears as the analysis temperature increases from 500 to 895 K. We attribute this temperature dependence largely to diffusion of oxygen atoms on the surface into the region where the electron beam is depleting them. This is supported by measurements in the absence of H_2 where a lateral concentration gradient is estimated by moving the sample after a lengthy period of e-beam bombardment. The "spot size" is larger for the higher temperatures. These results are indicative of the care which must be taken when electron spectroscopic methods are used to study kinetic phenomena involving surface oxides. We have made excellent progress in studies of the Ag/Rh(100) system [8]. The adsorption of Ag on Rh(100) at 300 K is characterized by uniform growth of the first monolayer. The desorption is characterized by two distinct peaks. The lower temperature state shows zero order kinetics and a desorption energy of 67 kcal mole^{-1} while the high temperature state shows first order behavior. The activation energy is slightly coverage dependent. Our data do not allow a unique description but a pre-exponential factor of 8.9 x 10^{12} sec^{-1} and an activation energy of 63.2 - 1.5θ_{Ag} kcal mole^{-1} is quite satisfactory. AES analysis can be used to establish the Ag coverage over the first monolayer. The initial dissociative sticking coefficient for O_2 is 0.8 at 530 and 680 K on clean Rh(100) while that for N_2O drops from 0.48 to 0.21 over this same interval. The saturation O(KVV) signal from O_2 is twice that observed for N_2O. The LEED patterns at saturation are c(2x2) and p(2x2) for O_2 and N_2O, respectively. Simple site blocking models adequately describe the influence of Ag on O_2 and N_2O chemisorption.

C. CURRENT RESEARCH PROGRAM

(i) Metal Semiconductor Interfaces

The Schottky barrier formed at a metal/semiconductor interface is one of the most important building blocks of modern semiconductor technology. The simplest approximation for a Schottky barrier is based on an abrupt interface between a pure semiconductor crystal and an epitaxial metal layer. However, a practical understanding of Schottky barriers must be based on the actual structure of the metal-semiconductor region [9-14], and in practical devices, the growth mechanisms must be understood in order to tailor parameters for particular applications. Research under this subunit heading (Metal Semiconductor Interfaces) is directed toward obtaining a detailed understanding of the structure, electronic properties and growth kinetics associated with metal semiconductor interfaces.

Our success in studying bulk $NiSi_2$ crystals formed epitaxially on Si substrates and our preliminary results on very thin nickel silicide layers indicates that there is a very good possibility for studying truly thin practical Schottky barriers. Our next objective will be to conduct a comprehensive investigation of the initial stage of compound formation at nickel-silicon interfaces. We will be interested in studying the stoichiometry, crystal structure and electronic structure of very thin nickel films deposited onto Si(111) and Si(100) crystal faces as a function of temperature from about 40°K up to 800°C where $NiSi_2$ forms. We have already shown that ordered silicides form on these surfaces when relatively thick (up to 1000Å) nickel layers are reacted, and we expect to be able to grow very thin ordered structures perhaps with several stoichiometries by suitable annealing processes.

The high degree of reactivity associated with silicide formation and the tendency of stoichiometric compounds to form suggests that at low coverages, one might expect "two-dimensional" features to appear in angle resolved photoelectron emission spectra. These features would characterize the electronic structure of a very thin (one or two unit cells thick) silicide. The formation of a thin silicide ordered layer should be observable using LEED. A specific current objective of our work is therefore to look for ordered silicide formation at very low coverages (1 to 10 Å). In this coverage range electron spectroscopy (UPS, AES, XPS and LEED) will be used to characterize electronic structures including binding energy and dispersion of electronic levels and to study structural changes as a function of initial substrate temperature and overlayer thickness prior to annealing. These experiments should lead to a better understanding of the initial growth of a silicide interface and should also help to provide additional insight into the possible existance of amorphous layers at silicon-silicide interfaces.

Experimental techniques based on electron spectroscopy are limited to applications involving only the top 10-20 Å because of the escape depth for electrons. Therefore very little is known about the structure and electronic properties of practical metal/silicon interfaces. Recent backscattering channeling studies have illustrated the utility of these methods to characterize the structure of thicker interfaces [15]. These techniques are able to probe for nonregistered atoms and have been used to study the structure and stoichiometry of semiconductor interfaces. To establish a comprehensive model of a practical interface, some electronic structure information is desirable to correlate with the structural information available from channeling.

We are planning to obtain information related to the electronic structure using optical reflectance techniques. Optical penetration depths are hundreds of angstroms, and the electronic structure is related to the dielectric constant which can be obtained from optical data. There is strong evidence that the silicide interface tends to be uniform except for perhaps 10-20Å at the metal/silicide or semiconductor/silicide junction. Dielectric models of a practical interface will not be too complicated. For example, it should be possible to obtain dielectric constants for a three layer system consisting of a top layer of $NiSi_2$, a thin region which is possibly glassy, and a Si substrate [2]. There is evidence based on UPS and AES that stoichiometry variations occur within 10 to 20 A of PdSi interfaces [16]. Similar variations are likely to be observed in $NiSi_2$ interfaces. We will attempt to correlate the interface models obtained from optical spectroscopy (dielectric constant as a function of depth) with our own studies based on electron spectroscopy, in particular AES depth profile results. Our overall objective will be to determine if optical spectroscopy can provide a nondestructive means of probing interface dielectric properties.

(ii) Surface Adsorbate Systems

Our EELS study of underlayer oxygen formation on Al(111)[6] opens a new area of application for EELS spectroscopy. Our current efforts are centered on attempts to obtain a more quantitative account of our Al(111)/O data. We observe three peaks in the EELS spectra for oxygen on Al whereas only two are expected based on the known structure of the system. To understand the origin of the third peak (which is small in comparison to the major peaks corresponding to surface and subsurface oxygen) we are modelling the oxygen and subsurface oxygen sites based on a 13 layer aluminum slab with Leonard-Jones force constants. This calculational procedure should permit us to model linewidths produced by mode coupling and peak positions. We hope to obtain a semiquantitative picture of the origin of the three peaks and their widths.

(iii) Non Reactive Metal/Silicon Interfaces

As mentioned earlier, no silver silicide is easily formed. However, diffusion of Ag into Si (or vice versa) has been reported at elevated temperatures (400°C) [17]. Furthermore, Au is reported by the same authors to form a silicide but only for overlayer thicknesses in excess of 15 Å. Our preliminary results disagree in the case of Ag-Si where we find no evidence for penetration on the basis of TPD data. This point must be pursued further by doing careful annealing experiments and modelling the AES and TPD results. In any case, it is agreed that room temperature deposition of Ag gives epitaxial Ag overlayers and no silicide. We plan to study the 2-D electronic structure of these thin layers using ARUPS. The case of Au is also very interesting since it appears that thin surface silicides could be formed or avoided simply by changing slightly the conditions of Au deposition and annealing. Such a system is attractive as a bridge between the very reactive systems like Ni-Si and the non-reactive systems like Ag-Si.

(iv) Metal/Metal Oxide and Metal/Metal Systems

The detailed description and understanding of interfaces between metals and metal oxides is an important materials problem in the sense that the growth and extent of such interfaces and layers have a marked effect on electronic properties. Our goal in this portion of the subunit is two-fold: (1) to develop techniques for quantitative surface analysis and depth profiling that are less destructive and capable of higher near-surface resolution than the standard sputtering/electron spectroscopic methods and (2) to make detailed measurements of the growth kinetics, the atomic and electronic structure using the techniques of in situ controlled submonolayer metal deposition, flash desorption, XPS, LEED, and AES, we intend to investigate such systems as $Al/Pt/O_2$ and $Ag/Rh/N_2O$. Our interest in the Al/Pt systems stems from our experience with oxygen on these two metals. Aluminum forms very stable oxides, while Pt does not. It does, however, form surface oxygen compounds under conditions where bulk oxides are unstable. We propose to examine in detail sub-monolayer to multilayer amounts of Al deposited on single crystal and polycrystalline Pt followed by exposure to either N_2O or O_2. From these measurements a reasonably detailed picture will emerge of what structures are formed and at what rates. In addition the electronic structure and the stability of various atomic structures can be evaluated in detail. As noted in our Progress section similar work is underway on Ag/Rh.

Depth profiling methods can also be used to analyze the growth of metal-silicides such as Ni, Pd, and Pt. This work will be pursued in parallel with the work described in section (1). The significance of the silicides in solid state devices makes this an important addition to our proposed work.

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III. QUANTUM ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE81-1 NONLINEAR WAVE PHENOMENA

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A. PROGRESS: This research unit is concerned with analytical and experimental studies of nonlinear wave interactions in physical systems. The work may be subdivided into two areas: (1) the development of digital time series analysis techniques useful in analyzing and interpreting fluctuation data generated by *nonlinear wave interactions* in various media, and (2) *nonlinear optics* in the infrared spectral region in molecular gases.

1. *Nonlinear Wave Interactions:* The objective of this work is to develop digital time series analysis techniques that enable one to properly analyze and accurately interpret experimental fluctuation data associated with nonlinear and/or nonstationary wave phenomena in a variety of media. One of the principal characteristics of any nonlinear system is the introduction of new frequency components, e.g., harmonics and intermodulation products. The "efficiency" with which these new spectral components are generated is given by an interaction or coupling coefficient. In the case of nonlinear systems where one can define an "input" and "output", the "efficiency" with which the new spectral components are generated is described by nonlinear transfer functions. For quadratically nonlinear interactions, the coupling coefficients or transfer functions are two-dimensional functions of frequency. For cubic interactions, the corresponding coupling coefficients or transfer functions are three dimensional functions of frequency. This clearly suggests that higher-order (i.e., multi-dimensional functions of frequency) spectral densities must be utilized to appropriately analyze and interpret fluctuation data associated with nonlinear physical systems. For a quadratically and cubically nonlinear system, the bispectrum $B(\omega_1,\omega_2)$ and the trispectrum $T(\omega_1,\omega_2,\omega_3)$ are the appropriate spectral densities, respectively. During the past year our research efforts have focused on the following topics summarized in subsequent paragraphs.

a. Nonlinear System Modelling in the Frequency Domain: The objective of this continuing effort is to investigate the practical aspects of modelling in the frequency domain the linear and nonlinear relationship between two physical fluctuating quantities x(t) and y(t). Let x(t) denote the "input" and y(t) the "output". Given two experimental observables x(t) and y(t), first one would like to ascertain whether x(t) and y(t) are linearly and/or nonlinearly related. Second, one would like to model the relationship between X(f) and Y(f) (the Fourier transforms of x(t) and y(t), respectively) with aid of a hierarchy of transfer functions. Although modelling in the time-domain has received a great deal of attention in the past several years, we have focused on the frequency domain since one can then relate the features of the model to relevant physical phenomena such as nonlinear wave-wave interactions. Also, the frequency domain approach allows one to generalize the concept of coherency, thus providing the experimentalist with a quantitative measure of the goodness of the linear, quadratic, and cubic nature of the model as a function of frequency.

In carrying out this work our approach has been to utilize the functional (i.e., integral equation) black-box approach. This approach is particularly appropriate when one has only the input and output time series data to work with, but no, or very incomplete knowledge, of the nonlinear differential equations characterizing the system. For nonlinear system modeling, there are two representations commonly discussed, the Volterra functional representation and the orthogonalized Volterra functional representation. In contrast to the majority of past work done in this area [1], which stressed the time domain, we have focused on a frequency approach, with particular emphasis on the orthogonalized functional representation. The frequency domain approach facilitates the computation of the nonlinear transfer functions through the use of the FFT algorithm and provides an interpretation of the nonlinear functionals in terms of wave-wave interactions. Furthermore, the difficult problem of so-called "diagonal integrals" in the time domain approach can be understood in the frequency domain in terms of self-interactions of waves or degenerate wave coupling. Lastly, the orthogonal functional model (involving a hierarchy of nonlinear transfer functions), provides a best fit between the model output and actual system output in a least-mean-square error sense. Our previous work on modelling the linear and nonlinear relationship between two fluctuations with the aid of a hierarchy of nonlinear transfer functions is described in Ref. [2]. Of particular importance is the fact that in Ref. [2], it is pointed out that the nonlinear transfer functions may be determined directly from the input-output data, by using FFT techniques to compute appropriate higher-order cross spectra (e.g., the cross-bispectrum, cross-trispectrum, etc).

We are currently applying this knowledge to the following three areas of technical importance: (1) electromagnetic wave scattering from nonlinear targets, (2) sea wave-induced nonlinear drift forces on moored-vessel systems, and (3) determination of aerodynamic transfer functions throughout the flight envelope. The "nonlinear" electromagnetic scattering work is being carried out under JSEP sponsorship, while the latter two projects are sponsored by other agencies. For this reason we briefly review the scattering applications.

A number of man-made objects, which are to be detected by radar, exhibit nonlinear effects which result in new frequency components (e.g., intermodulation products, harmonics, and "degenerate" frequencies) appearing in the backscattered field. In a recent paper [3] we presented a conceptual model which allows one to systematically characterize nonlinear scatterers in terms of a hierarchy of linear, quadratic, cubic, etc. radar cross sections. The concept of "nonlinear" cross sections allows one to generalize the radar equation for a nonlinear target. This "nonlinear radar equation" may be regarded as a generalization of the harmonic radar equation [4]. In Ref. 3 it was pointed out that the various nonlinear radar cross sections can, in principle, be computed, in terms of higher order spectral density functions, from the transmitted and scattered signals. Our most recent efforts, based on numerical simulation, have been concerned with the practicality of applying these concepts to nonlinear scatterers. Our preliminary results were described at a National Radio Science Meeting [5] and our most recent results are tentatively scheduled to be presented at the RADAR-82 Conference in London [6]. Specifically, both of these papers deal with the practical details surrounding the digital implementation of higher order spectral analysis required to analyze backscattered data from nonlinear targets. The results of a computer simulation of scattering from a target containing both linear and cubic features supports the validity of the approach described in Ref. [3]. Of particular interest is the result that the cubic nature of a target may be detected and investigated by appropriately processing the return at the fundamental frequency, rather than at the third harmonic. For a target containing both linear and cubic features, the return at the fundamental frequency ω_o will consist of two parts. The first is due to the linear nature of the target, the second due to the cubically generated degenerate component at ω_o (i.e., the ω_o component in the expansion of $\cos^3\omega_o t$). We have demonstrated how digital cross-trispectral analysis may be used to isolate the degenerate signal at ω_o from the linear return, even though both components are at the same frequency. Finally, results describing the relative insensitivity of the approach to low signal-to-noise ratio has been demonstrated. This relative insensitivity is primarily due to the fact that the approach rests upon a novel method (based on the properties of the cross-trispectrum) to detect phase coherence, rather than on the absolute amplitude of the signals of interest.

b. Experimental Determination of Quadratic Coupling Coefficients: Previously, we have reported on attempts to identify [7] and quantify [8,9] using digital bispectral analysis, the presence of wave-wave interactions in a fluctuation spectrum. These earlier results obtained under JSEP sponsorship are now being utilized in an NSF sponsored study of the role of nonlinear wave-wave interactions in the evolution of turbulence in fluids [10-12]. The transition to turbulence is characterized by the appearance of new spectral components and the continual redistribution of energy among existing and new spectral components. In those cases where a three-wave coupling model is appropriate we have shown that such spectral energy transfers may be estimated using digital bispectral analysis techniques to determine coupling coefficients and power transfer functions [10-11].

c. Experimental Determination of the Joint Power Spectrum $P(k,\omega)$: Although this work does not involve nonlinear phenomena per se, it does involve one of the fundamental diagnostic problems involving the physical interpretation of fluctuation phenomena. In order to more completely describe a space-time fluctuation, one needs to estimate the joint wavenumber-frequency power spectrum $P(k,\omega)$ which characterizes the spatial and temporal properties of the fluctuation. We have finished developing a digital method for estimating the joint power spectrum, which requires measurements at only two spatial points for a one dimensional fluctuation. The work will appear in Journal of Applied Physics [13]. The key idea is to determine the fluctuation power in the joint intervals $(k, k+\Delta k)$ and $(\omega, \omega + \Delta\omega)$, where k and ω denote the wavenumber and frequency, respectively. Specifically, we introduce the concept of the local wavenumber and frequency spectral density, which can be estimated using spatially fixed, point data sources ("fixed probe pairs");

and describe the relationship of this spectral density to the conventional wavenumber and frequency spectral density and the cross power spectral density. The local wavenumber and frequency spectral density is shown to be equivalent to the conventional wavenumber and frequency spectral density when the fluctuation is stationary and homogeneous and consists of a superposition of wave packets; such a fluctuation is the basic model used in many turbulence theories. A digital method for estimating the local wavenumber spectrum has been developed and applied to the study of drift wave turbulence in an rf-excited discharge. The statistical dispersion relation and wavenumber spectral width, computed from the local wavenumber and frequency spectrum of the drift wave turbulence, are compared with the conventional spectral moments computed using the correlation method of Iwama and Tsukishima; good agreement is found over a wide range of frequency. A frequency integrated wavenumber spectrum is computed; both frequency and wavenumber spectral indices are found independently. The local wavenumber and frequency spectrum is a completely new approach to the use of fixed probe data, and we believe it can greatly extend the quantity of information available from fixed probes, which are the principal tools in many, if not most, fluctuation experiments. It should be emphasized that the technique will be equally useful in studies of space-time fluctuation phenomena in solids, liquids, and gases. We are currently investigating the feasibility of utilizing these techniques to study the space-time characteristics of 1/f noise in thin metal film resistor arrays.

d. Three-Wave Nonlinear Optical Interactions in Dispersive Media: This work was also completed and published recently in IEEE Journal of Quantum Electronics [14]. We treated in detail the situations corresponding to the presence and the absence of dispersion in the medium. For each of these situations, both the degenerate and nondegenerate cases were considered. For all of the situations considered, we have chosen to work within the framework of a realistic and specific numerical example of an OPA, consisting of a $LiNbO_3$ crystal illuminated by a pulsed pump of amplitude FWHM = 30 ps, $\lambda = 1.064\mu m$, having a peak intensity of $10^{14} W/m^2$.

We enumerate below the major results of this study. The most important and novel result is that the presence of dispersion leads to the formation of a substructure in the parametrically amplified signal when pump depletion is permitted. In a $LiNbO_3$ crystal of length 3 cm with an initial pump intensity of 10^{14} W/m^2, very narrow $\sim$1.6 ps, and intense $I_s \simeq 0.8 I_{po}$ pulses appear in the substructure. Experimentally, such a substructure with ultrashort components has been reported by Kryukov et al. The nonlinear medium in their experiment was $LiIO_3$ in the form of two 2 cm long crystals. With L_{NL} = 0.66 cm and $I_{po} = 10^{14}$ W/m^2, the length necessary for the substructure formation to commence is $L_s \simeq$ 1.0 cm and for distinct subpulses to be observed, $L_s \simeq$ 2.0 cm. These values are within the range of the experiment mentioned above.

Analytical study of the nondispersive degenerate case indicated that a two-pulsed substructure is formed. This substructure commences when pump regeneration begins and the pulses result from a depletion of the signal pulse. Depletion continues with the signal vanishing and the pump becoming completely regenerated asymptotically. In the presence of dispersion, as noted previously, a multipulse substructure arises. In addition, the process exhibits a periodic transfer of energy between the pump and the signal, in marked contrast with the nondispersive case. The period diminishes with increasing propagation distance in the nonlinear crystal and with increasing values of the dispersion coefficient.

The nondispersive nondegenerate situation also exhibits such a substructure. However, in contrast to the degenerate case, the number of subpulses continues to increase. A similar effect is observed for the dispersive case. Oscillatory energy transfer between the pump wave and the other two waves is observed. This result is known for the nondispersive case. However, the interesting feature of the nondegenerate case is that the behavior of the energy transfer is almost the same for both the dispersive and the nondispersive cases. This is to be contrasted with the behavior in the degenerate regime. Analysis of the dispersive cases shows that the dispersive effects are separable to an extent and that the evolution of the solution is basically controlled by the nonlinear interaction terms.

Work on *Nonlinear Wave Interactions* will continue with emphasis on scattering from nonlinear targets, utilization of $P(k,\omega)$ spectral densities to investigate the space-time statistics of 1/f noise. Related work involving the measurements of aerodynamic transfer functions and studies of nonlinear wave interactions in the transition to turbulence are supported by the USAF Armament Technology Laboratory and the National Science Foundation, respectively.

2. *Nonlinear Optics:* The objective of the continuing research in *nonlinear optics* is to study new types of resonant optical nonlinearities in molecules at infrared wavelengths. This research employs optical third harmonic generation (THG), multi-photon absorption and degenerate four wave mixing (DFWM) to measure the nonlinear properties of two classes of molecules; those with a single two-photon resonance and those that are at least approximately triply resonant. When this technique is used with a step-tunable CO_2 laser, the spectral dependence of the nonlinear susceptibility, its magnitude, and the influence of limiting processes can be measured. The work this year focuses upon degenerate four wave mixing in triply resonant SF_6, and the conclusion of the study of THG in CD_4. Both cases emphasize narrow and strong resonant processes.

A series of THG experiments have been performed on CD_4 at room temperature and at 193K, exciting with the P(8) through P(16) lines in the 9 micron band of a CO_2 TEA laser. The room temperature results have been published [15] while a complete publication is still being prepared. We measured the THG dependence on gas pressure and fundamental laser power for each of the indicated laser lines. Due to fundamental absorption at about J=20 on the tail of the ν_4 absorption band, the maximum THG signal occurred at 300 Torr pressure. At lower pressures, a factor of three enhancement in THG was observed compared to CO.

The first results suggest double benefits to be gained by cooling the gas. First, the high J absorption of the fundamental should decrease dramatically; the second the Raman spectrum in the vicinity of the two-photon resonance should simplify. The result should be higher ultimate conversion efficiency in the first case, and a more easily interpreted THG spectrum, with possibly higher conversion, in the second case.

Experimental data confirms these predictions. The absorption did fall below the measurement limit, and the THG efficiency did increase by a factor of 3-4 depending on laser frequency. Modeling of this data is still underway and a publication is being prepared.

An experimental study of degenerate four-wave mixing (DFWM) in SF_6 gas was also undertaken. DFWM and the accompanying losses were studied for the P(8) through P(28)

CO_2 laser lines in the 10 micron band. Parameters were gas pressure, buffer gas mix, and pump wave intensity.

The main objective of the work was to model and to verify experimentally the cause of the sudden drop in conjugate reflection efficiency for increasing gas pressures. Both increased absorption of the pump beams and the pressure broadening of the resonances were suspected.

Most of the experimental results were obtained with an experimental configuration with a retro-reflected pump wave. The backward travelling pump is allenuated by two passes through the gas cell. A symmetic configuration with identical pump waves was also used and showed qualitatively similar behavior to the retro-pump configuration. All modeling was done for the retro-pump case.

Experiments with N_2 as a buffer gas showed only a small, slow variation in conjugate reflectivity and absorption as a function of pressure. Thus, pressure changes in the resonance lines was eliminated from the model.

The final model which gave a good fit to the drop in conjugate reflectivity versus pressure, considered spatially dependent saturated absorption of the pump waves. The saturated absorption of the gas was first measured using conventional techniques. The intensity of the pump waves at any point in the saturable absorber can be determined. By an integration over the interaction length, the conjugate wave amplitude and reflectivity was then obtained. Pump wave depletion is included. Peak conjugate wave reflectivities of up to 27% were measured.

During the course of this work, a similar study was published by workers at Hughes Research Labs [16] which duplicated much of our work, particularly the variation of the conjugate reflectivity with laser frequency. Our model for the effects saturated pump wave absorption and pump wave depletion remains as a unique result of this project.

Research on new nonlinear optical processes and materials will continue. Emphasis will shift from gas phase molecules to solid state materials, chiefly semiconductors with near band-gap infrared laser excitation. The nonlinear processes in these materials, particularly multiphoton absorption, contribute both to the optical damage and to the melting and annealing of these materials. Our research will pursue an understanding of these high energy laser-material interaction processes.

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THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
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A. RESEARCH OBJECTIVES The experiments done in our research unit emphasize structural and dynamical studies of molecular systems using non-linear interactions with electromagnetic radiation for detection and/or for state-selective excitation. The scientific objectives are (1) additional knowledge of the basic process of non-linear interaction of matter with light, (2) development of non-linear techniques as dynamical probes, (3) structural studies of excited states of molecules and ions previously unavailable for study, and (4) studies of energy transfer processes in both collisional and collision-free environments. These objectives will be pursued under three research efforts: non-linear scattering of electromagnetic radiation, inelastic and superelastic scattering of electrons from excited states produced selectively by laser excitation, and dynamical studies of excited molecules produced by multiphoton excitation.

B. PROGRESS:

1. Electron scattering from excited molecules. In the study of atoms and molecules by electron scattering, three main processes yield detailed information about the target. Inelastic scattering involves a transfer of a portion of the energy of the incident electron to the target, elastic scattering involves a change in direction of the incident electron without a change in energy, and superelastic scattering involves a transfer of energy from the target (if it is in an excited state) to the scattered electron. In addition, total scattering (inelastic plus elastic) can yield a great deal of information, when used in conjunction with the proper theory. The measurement of these four types of scattering is useful in several energy ranges: low energy, involving 1-1000 eV electrons, medium energy with 1-10 keV electrons, and high energy with electrons of energy 30-50 keV. Each energy range has its own area of contribution to knowledge about the molecule or atom in question.

The differential cross sections for electron scattering at high incident energies can be considered to be the Fourier transform of the orientationally averaged electrostatic molecular potential function of the target gas. In our latest studies we have concentrated on the anharmonic force constants in the potentials of SF_6, CO_2 and SO_2. We have shown that the molecular force constants of the latter two derived from spectroscopic data are compatible with our results while the SF_6 potential is still quite inaccurate [1,2,3]. This work was initiated with JSEP support and is now funded by the NSF.

Inelastic scattering at all energies has been known to be a valuable tool in understanding the excited electronic states of atoms and molecules for many years. Pioneering work by Geiger [4] at high energies and Lassettre [5] at low energies has shown the value of this technique. In the past fifteen years much work has been done in this field, and new techniques have been developed to the point where significant contributions can be made to the understanding of the electronic states of atoms and molecules.

A relatively unexplored field is the counterpart to inelastic scattering; superelastic scattering. Although the electron beam apparatus is exactly the same as that used for inelastic scattering, the necessity of a laser as the excitation source and the extra technological problems of a three beam (electron, gas, and laser) crossed-beam experiment make superelastic scattering a much more difficult process to measure. However, a good deal more information stands to be gained from it. Just as inelastic scattering can determine the selection rules of the transitions from the ground state by observing the angular dependence of the intensities, superelastic scattering can determine the transitions from the excited state. This gives direct information about the excited state. One can, for example, observe the transfer of energy from one excited state multiple to another via L-S coupling at a Fermi resonance. Also, since the laser is a very monochromatic light source, the high resolving power of optical spectroscopy is realized in the excitation of a specific molecular state. This helps to overcome the resolution limits of ordinary inelastic scattering.

The feasibility of superelastic scattering having been established in experiments using Na, Ba, and O_2 [6,7,8], we have started our investigation of superelastic scattering with the molecules NO_2 and I_2.

Significant progress has been made on two fronts. We have shown that our newly designed low energy electron gun is capable of producing intense (10 micro amp) electron beams as low as 100eV. However, the true novelty lies in the fact that the energy distribution in the electron beam is dominated by a Maxwell distribution determined by the temperature of the emitting tungsten filament. The common anomalous energy spread (often referred to as the BOERSCH effect) has been avoided by the careful design of the electron optics. The lenses were adjusted so that no beam cross-overs with high electron densities were produced and thus only the theoretical minimum of additional energy spread has to be tolerated. This achievement is particularly important to our proposed experiment since the electron beam has to be monochromized in order to resolve the vibrational states of the molecules. This means only a slice of the energy distribution function can be used. Thus the intensity of the selected electron beam will be reduced at the same rate as the original beam energy distribution widens.

The experimental results were confirmed with a computer program which calculated the electron trajectory including all aberrations and the effects of the beam's space charge. This program was kindly provided to us by Dr. Hermannsfeld at SLAC [9]. The experimental and theoretical results have been published in Ref. 10. We are confident that this study is a significant step forward in the technology of LEED (low energy electron diffraction).

The second area where we made important progress is our laser facility. Preliminary studies in optical pumping efforts showed that the spectral density of a simple linear dye laser is far to small to saturate even the few molecules which are in the suitable vibrational-rotational states to participate in the excitation. During the last few months the dye laser was modified by adding a Michelson interferometer. The resulting light is a single mode (about 50 MHz width) and intensities up to 800mW can be reached. The pumping efficiency is further enhanced by the use of a multipass cell with a common focal point [11] by a factor of 50.

2. Collision-induced light scattering of the rare gas like diatoms was investigated [12,13]. For the first time, polarized collision-induced scattering was observed of the argon, krypton and xenon diatoms, and models of the trace of the diatom polarizability tensors obtained [13,14]. At the same time, the most accurate empirical anisotropy functions for all rare gas pairs are obtained and compared with the ab initio computations where these were available [12]. Particularly the state-of-the-art configuration interactions (C.I.) calculations could be critically compared with the

new measurements [15,16]. A long-standing uncertainty concerning the argon diatom light scattering cross section could be finally resolved [17], which is significant as essentially all measurements of collision-induced scattering intensities can now conveniently and accurately be referenced to argon. Collision-induced absorption profiles were also computed for several rare-gas mixtures, based on the ab initio induced dipole moments available [18]. Whereas in HeAr and ArKr mixtures the agreement of the experiments with the fundamental theory is very good, typically better than 10%, for the NeAr mixture a stark disagreement is observed, which must be due to inaccuracies of the semi-empirical interaction potentials used to calculate the line shapes. A refined repulsive NeAr potential is obtained [19]. As an aside, the photon-assisted recombination of hydrogen atoms could be investigated for the first time, using the computer codes developed previously for this program [20].

Finally, the computer codes used for the evaluation of collision-induced scattering [21] (CIS) could be modified to also account for collision-induced absorption (CIA). Collision-induced absorption was first observed by Kiss and Welsh [22]. We use as input the ab initio collision-induced dipole moments obtained by Byers Brown and coworkers [23,24] to compute from the adiabatic, wave mechanical theory spectral profiles for direct comparison with the measurements [25]. Whereas in most cases a most satisfactory agreement is observed, for neon-argon mixtures a substantial inconsistency was seen, but not yet understood. More work is required to shed light on this serious inconsistency, which seems to affect all mixtures with neon [18].

3. <u>Energy transfer reactions</u> are being studied at large pressures following selective excitation of atoms and molecules by two-photon laser excitation. Traditional studies of the excitation transfer have emphasized studies of the microscopic behavior of energy transfer in two-body collisions at low pressures. At liquid densities, reactions are usually limited by transport of the reactants; and microscopic interactions at short ranges are relatively unimportant. In high pressure gases one might observe the effects of transport and the alteration of microscopic reactions by three body collisions (termoleculor reactions).

Previous studies of energy transfer in rare gases have been conducted using electron impact excitation [26,27,28,29] as a means of depositing energy. This method suffers from a lack of selectivity. Some other excitation mechanisms that have been used are discharge combined with single-photon excitation [30,31] and single-photon excitation [32]. The discharge method is restricted to pressures below 20 Torr.

The use of two photon absorption as a means of selective excitation [33] offers several advantages over the other excitation techniques. This method can be very selective if narrow band lasers are used. Indeed, Doppler-free spectroscopy can be conducted to reveal very fine detail in the absorption profile. Many states can be accessed via two photon absorption since transitions of $\Delta J=0, \pm 1, \pm 2$ are allowed. There is no limit on the pressure range for the sample-even liquid and solid phases can be studied.

The use of state selective excitation in the measurement of energy transfer rates results in simplification of the data analysis and minimal computer modelling. The fluorescence from the excited state and states produced by collisions is used to monitor the transfer rates. Branching fractions and energy disposal are determined by measuring the ratio of the integrated intensities of each of the fluorescent states to that of the excited state. We will measure transfer rates with a tunable, modelocked c.w. dye laser. Because of the high spectral intensity of this laser (1.56×10^{10} photons/pulse-A at 5×10^6 pulses/sec) the number of excited states produced by two-photon absorptions should be nearly equal to the number produced by resonant absorption of synchrotron radiation (3×10^3 ph/pulse/A). Because of the high repetition frequency of this laser our single photon correlation technique remains an accurate method for studying the time dependence of the fluorescence and decay times as short as 20 psec should be measurable.

Initial experiments have begun with studies of collision processes of the 6p manifold of xenon following two-photon laser excitation. These experiments use a dye laser pumped by a nitrogen laser. This laser has been used with a 20 GHz linewidth to study linebroadening of the $2p_5$, $2p_6$ and $2p_9$ for large wavelength ranges at pressures from 10 Torr to 10,000 Torr [34]. With the use of this high power laser (> 100 watts of ultraviolet radiation in a 5 nanosecond pulse) a large flux of photons reaches the photodetector. The flux produced is large enough that the response time of the photomultiplier makes single photon counting techniques impossible, but small enough to make usual analogue techniques impractical.

We have developed a detection scheme based on digitizing the charge at the photodetector for the first 100 nsec following excitation. This charge is divided by the mean charge for a single photon event and added to individual photons counted at later times. This enables the detection of up to 900 photons per laser pulse. This signal is limited by the linearity of the photomultiplier. We have found the precision of this detection system to be limited by Poisson statistics for signals from 10^{-2} to 900 photons per laser pulse. Our noise levels are limited by scattered light to levels of 5×10^{-3} photons per laser pulse.

We have measured fluorescence spectra near 828 nm produced by excitation of $2p_5$ at various pressures. Similarly, we have observed fluorescence of $2p_6$ near 823 nm and $2p_9$ at 905 nm. At low pressures, energy disposal is primarily via photoemission and some radiationless quenching by ground state atoms. At higher pressures, mixing within the manifold starts to populate several other states in the same manifold. A comparison of the integrated fluorescence intensities from all populated states enables us to determine the degree of mixing and other deactivation processes. Excitation spectra were also obtained by scanning the laser while monitoring a single fluorescence line. We now have a significant number of excitation spectra of $2p_5$, $2p_6$, and $2p_9$ for pressures from 1000 to 10,000 Torr. These continuum spectra are shifted to the red which suggest they result from either the population of bound excimers dissociating to the above atomic levels or they are transitions from the repulsive part of the lower dimer levels to less repulsive excimer surfaces. These results were recently reported at the DEAP meeting [35] and a Ph.D. dissertation [36].

We have also observed dipole-quadrupole two-photon transitions to $5p^5 5d[7/2]_3$. This transition is 3 1/2 orders of magnitude less probable than the dipole-dipole transitions to $2p_5$, $2p_6$ or $2p_9$. In Fig. 1, we show a broad scan indicating the observed transitions. As well in Fig. 1 we observe a weak continuum between $2p_5$ $(6p[1/2]_0)$ and $2p_6(6p[3/2]_2)$. This feature is near the $5p^5 5d[7/2]_0$ state which is forbidden even in dipole-quadrupole approximation. At intermediate internuclear separations, however, this state crosses repulsive curves from $2p_6$ and $2p_8$; hence we would expect larger two-photon transition rates at smaller inter-

internuclear separations near crossings. This model is supported by the observations that larger rates for production of $2p_8$ by collisions are observed when the pump laser is tuned near the crossing than when it is tuned at either $2p_5$ or $2p_6$.

Precision excitation spectra in the wings of $2p_5$, $2p_6$ and $2p_9$ have been measured for several pressures. These spectra will enable determination of potential surfaces for excimer states with two photon allowed configurations. We have also obtained high resolution (750 MHz) spectra of the line shapes in both the line core and wings at pressures up to 760 Torr. These spectra have sufficient precision to test recent unified line shape theories when applied to our experiments [37].

We have continued with efforts toward using the synchronously pumped dye laser for time dependent studies. We have mode locked the u.v. lines of the argon ion laser and succeeded in obtaining picosecond pulses from Stilben 3 dye. To date we have obtained 6 mW average power at 440 nm pulse widths on the order of 20 psec and a repetition rate of 6 MHz. The doubled power from this laser is currently insufficient for the two-photon experiment. We are now trying to increase the pump power available in the u.v. from our ion laser by using an all-lines mode locker, and we have reduced the dye laser cavity loss by using birefringent filters rather than a wedge for tuning. Tests are now in progress.

C. FOLLOW-UP:

1. One major barrier has to be overcome before the scattering experiment can be tried again. When the molecules exit the beam-forming nozzle, they are at room temperature with the accompanying Boltzmann distribution for the occupation of the rotational and vibrational states. Due to the relative high density of states, the number of molecules in our scattering target occupying a particular state is very small. Since we estimate that we need to excite about 5% of the molecules we plan to cool the gas target using the adiabatic cooling which occurs in supersonic nozzles. NO_2 has been cooled successfully in this way before with the internal temperatures dropping to 80°K for the vibrations and 10°K for the rotations. Unfortunately, this molecule tends to form dimers and nothing is currently known about the dimer concentration in these supersonic jets. Therefore, we are presently engaged in rebuilding our vacuum system to handle a supersonic jet assembly and are installing our quadrupole mass

spectrometer to cope with these questions.

2. Summarizing, it is seen that our work concerning CIS of the monatomic gases has come to its conclusion. Two major review articles describe our efforts in this field [12,18]. The related CIA study [18] of rare gas mixtures provided an interesting extension of our goals and is also considered complete at this time. Currently, our new measurements concerning simple molecular gases are being evaluated and will be compared with the fundamental theory, while preparations are being made to measure certain non-linear properties of collisional pairs of atoms and molecules.

3. We propose to continue studying energy transfer and quenching of xenon excited atoms and excimers. Some effort will be directed to the analysis of the excimer spectra we are now obtaining in pure xenon gases. New experiments will study excitation transfer in other rare gas buffers. Particularly interesting is the possibility of studying "forbidden" excitation transfer from xenon atoms and excimers to krypton. Two reactions are possible

$$Xe(5p^5 6p) + Kr(4p^6) \rightarrow Xe(5p^5 6s) + Kr(4p^6)$$

$$Xe(5p^5 6p) + Kr(4p^6) \rightarrow Xe(5p^6) + Kr(4p^5 5s)$$

The first reaction should have a small cross section because a large electronic energy must be transferred to translational motion of the Kr atom. The second reaction is "forbidden" because a quadrupole term in the scattering potential is required to deactivate the xenon atom.

We have completed construction of a new sample chamber and optical elements for two-photon excitation studies of liquid and solid xenon. Experiments on this chamber will also begin in the coming contract year. Line broadening of xenon excimers will also be studied at low pressures and temperatures; where bound-bound transitions may be observed.

We are also constructing a new chamber where mixed gases can be flowed while maintaining high pressures. Flowing of the gas will remove dissociation products produced when studying energy transfer to molecular dopants. These dopants will allow the measurement of energy disposal in vibrational and rotational levels of product states.

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THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE81-3 COLLECTIVE EFFECTS IN NONLINEAR OPTICAL INTERACTIONS

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A. OBJECTIVES AND PROGRESS: The objective of this research unit is to investigate certain collective aspects of the nonlinear interaction of gas-phase atoms with resonant electromagnetic radiation. Particular emphasis is placed upon the study of "simple" systems, that is to say physical systems that are on the one hand experimentally realizable and which are on the other hand amenable to detailed microscopic analysis. For such systems one can hope to address the question of the contribution of microscopic quantum fluctuations to macroscopic phenomena.

Following this general guideline we have devoted our principle effort over the past year to a study of the cooperative nature of resonance fluorescence in optical bistability with "two-level" atoms. Interest in the field of optical bistability arises from a number of distinct points of view [1,2]. First of all, from the point of view of fundamental studies of the interaction of radiation and matter, theoretical investigations of optical bistability have served to extend our understanding from single-atom resonance fluorescence to a case in which collective atomic fluorescence can play a dominant role in determining a system's evolution. In the general context of the study of the fluctuation and relaxation processes for nonlinear systems driven far from thermal equilibrium, optical bistability has received attention due in part to the close resemblence between the hysteresis cycles of optical bistability and of ordinary first-order phase transitions [3,4]. Finally there is the potential that bistable devices might serve as building blocks for optical signal processing systems, as for example in an optical communications network.

Of the numerous schemes for achieving bistable switching (including electronic feedback, reflection at a nonlinear interface, and self-focusing), the subject of our research is the bistability that results from the coupling of an optical nonlinearity to the repeated reflections inside a Fabry-Perot or ring resonator. As previously mentioned, the source of the optical nonlinearity for our experiments is chosen with an eye toward a system of the greatest conceptual simplicity. By undertaking experiments involving "two-level" atoms, we are making an investigation of optical bistability free from certain "complicating" features such as inhomogeneous broadening, optical pumping, or other nonradiative relaxation mechanisms. The theoretical descriptions for such a system of two-level atoms are numerous [5-10] and predict a wide range of phenomena which are of relevance to each of the areas listed above. However in spite of the rather advanced state of development of the theory almost no experimental information is available for a bistable system comprised of homogeneously broadened, two-level atoms inside an optical resonator [11,12]. The intent of our research is to address experimentally several questions that until now have been treated only theoretically for bistability in the "simple" arrangement of two-level atoms inside an optical resonator.

Our JSEP research is divided into three sequential phases. At present we are pursuing an investigation of the deterministic, steady-state regime in optical bistability. The bistable system consists of a well-collimated atomic beam passing through a high finesse optical resonator. The atomic beam is optically prepumped to produce "two-level" atoms [13,14] and is optically dense ($\alpha\ell \sim 1$). The characteristics of the output versus input intensity to the resonator are recorded for various densities of the atomic beam and for resonant and nonresonant atomic and cavity detunings. A comparison of these results to current theoretical predictions is being made to assess the importance of transverse effects, of standing-wave effects, and of small instabilities in laser frequency or cavity length.

The second phase of our work is to be directed toward measurements of the fluorescent spectrum in optical bistability. Such measurements will provide a step beyond the deterministic understanding of optical bistability and will begin to address the question of the stochastic nature of the switching process. As the recent work of Carmichael [15] and of Lugiato [16] demonstrates, so far as the fluorescent field is concerned, the dynamics of single-atom resonance fluorescence are reproduced with cooperative corrections entering only to order 1/N (N = number of atoms inside the resonator). Our preliminary experiments will be directed along the lines of earlier work in single-atom resonance fluorescence [17,18] to confirm the prediction of Carmichael and of Lugiato [15,16]. Subsequent experiments will explore the behavior of the spectral density of the fluorescence from the atoms inside the optical cavity in the region of critical density for bistability. In this domain of large differential gain the linearization procedures used in all theoretical analyses of the spectral density in optical bistability are of questionable validity [19], and one might expect substantial departures from the single-atom theory. It is in this region of critical C (with C = cooperativity parameter of Bonifacio and Lugiato [7]) that any aspects of cooperativity in optical bistability should be apparent.

The third phase of the research program will study the instabilities in optical bistability that lead to self-pulsing (continuous light in, pulsed or chopped light out). This is an area of intense current activity since states that were once thought to be stable against perturbation are now predicted to be unstable. A number of different physical mechanisms can be responsible for these instabilities, including those discussed by McCall [20], Ikeda [21], and Lugiato [5]. It is our intent to investigate experimentally the self-pulsing instability treated by Lugiato and coworkers [5]. We should note that the physical origin of this self-pulsing appears to be quite distinct from that responsible for the period-doubling bifurcations predicted by Ikeda [21]. As shown by Carmichael et al. [22] the Lugiato and Ikeda instabilities arise in distinct limits from a common characteristic equation, with the limiting process for one type of instability seeming to exclude the other. Our experiments will be directed toward a mapping of the domain over which self-pulsing occurs and an analysis of the temporal and spectral features of the self-pulsing.

For our investigation of optical bistability as outlined above we have developed an apparatus consisting of the following three essential elements: (1) a well-collimated, optically thick atomic beam to serve as a nonlinear medium (2) a frequency stabilized, tunable dye laser for resonant excitation, and (3) an actively stabilized confocal resonator through which the atomic beam passes. Our initial investigations of optical bistability have been directed toward a study of the variation of the hysteresis curve of transmitted intensity versus incident intensity as a function of atomic density for near zero laser and cavity detunings. For the atomic beam densities available from our apparatus and for an empty cavity finesse of 300, we are able to explore a large range of atomic cooperativity [7]. In absorptive bistability this range allows us to record the development of the input-output characteristics from well below to well above the critical value for bistability. Figure (1) is the result of recent measurements that we have reported [23,24] which shows such a development, beginning with the onset of bistability and leading to a point of fully developed hysteresis.

To our knowledge these data represent the first observation of the evolution of the steady-state hysteresis cycle in absorptive optical bistability and as such are the most significant achievement of our program over the past year. A preliminary comparison of our data with theoretical treatments that incorporate transverse effects [25,26] is shown by the full curve in Figure 1. This comparison indicates reasonable agreement between the predicted and observed values of critical C, but reveals a discrepancy between calculated and measured switching intensities with the measured intensities roughly 80% higher than expected. The source of this discrepancy is not understood and is the subject of further investigation.

The experimental problems remaining in our study of the deterministic regime in optical bistability relate to the long and short term stability of the optical resonator used in these experiments. A mechanical instability in the length of the resonator of about one part in 10^9 limits the sweep-to-sweep reproducibility of our data. In an effort to improve the short-term stability of the cavity, a new optical resonator has been fabricated in our machine shop. Preliminary work indicates that this new cavity should provide a factor of 20 improvement in passive short-term stability. For further improvement of the short-term stability and for absolute control of the length of the cavity over long times, a servo loop is to be employed to lock the transmission function of the cavity to an external reference laser. The reference laser is a Mark-Tech Model 5800 Lamb-dip stabilized He-Ne laser. Not yet implemented is a scheme for providing tunability of the reference laser frequency with an acousto-optical modulator to explore the dependence of bistability on the cavity detuning θ. By tuning the reference laser frequency, the stabilized length of the bistable resonator will be varied relative to a given length ℓ_0, with ℓ_0 equal to a length for a transmission maximum for the empty cavity at the atomic resonance frequency.

Other experimental problems associated with our measurements are those of laser intensity and frequency stability and of maintaining a two-level atom at high intracavity intensities. With regard to laser frequency stability, we have initiated a project to reduce the linewidth of our dye laser from 250KHz rms to a value closer to 10KHz through the use of an intracavity electrooptic modulator. As well an intensity stabilization unit utilizing an electrooptic modulator external to the laser cavity is to be used to reduce the intensity fluctuations of the dye laser to an rms level below .5%. With regard to the question of maintaining a two level system at high intracavity intensities, we note the conclusions of Citron et al. [14] who found that small magnetic field inhomogenities and slight deviations from a state of precise circular polarization can cause the two-level scheme to break down at high field strengths. Our preliminary investigation of this problem is encouraging and is the subject of a recent report [29].

From our preliminary observations in our atomic beam apparatus, we propose to extend the work to make a systematic investigation of the steady-state parameter dependences in optical bistability. Initially for absorptive bistability (zero detuning between laser and atomic resonance frequencies) and subsequently for dispersive bistability, the values of the turning points of the hysteresis curve for both incident and transmitted intensity will be recorded as functions of C. In the interpretation of our results we will attempt to address each of the three following issues: the validity of the mean-field model for our system [7], the role of standing-wave effects in optical bistability [30], and the influence of transverse effects in producing either changes in the hysteresis curve or alterations of the actual spatial structure of the transmitted beam [25,26]. Given the appropriate theoretical context in which to frame our measurements, we will next turn our attention to certain dynamical processes in optical bistability, as previously discussed.

Although still in an early stage this work on optical bistability has yielded significant results (Figure 1 is the first such measurement of its kind). With the support of the Joint Services Electronics Program I certainly plan to continue this investigation to explore the analogy between nonequilibrium phase transitions and optical bistability, to study the time-dependent dynamics in optical bistability, and hopefully to address the question of the role of intrinsic quantum fluctuations in optical bistability. As the research program grows, outside funding is being sought for various aspects of the project. A proposal is currently under review at the National Science Foundation relating to work that has been started under the auspices of JSEP.

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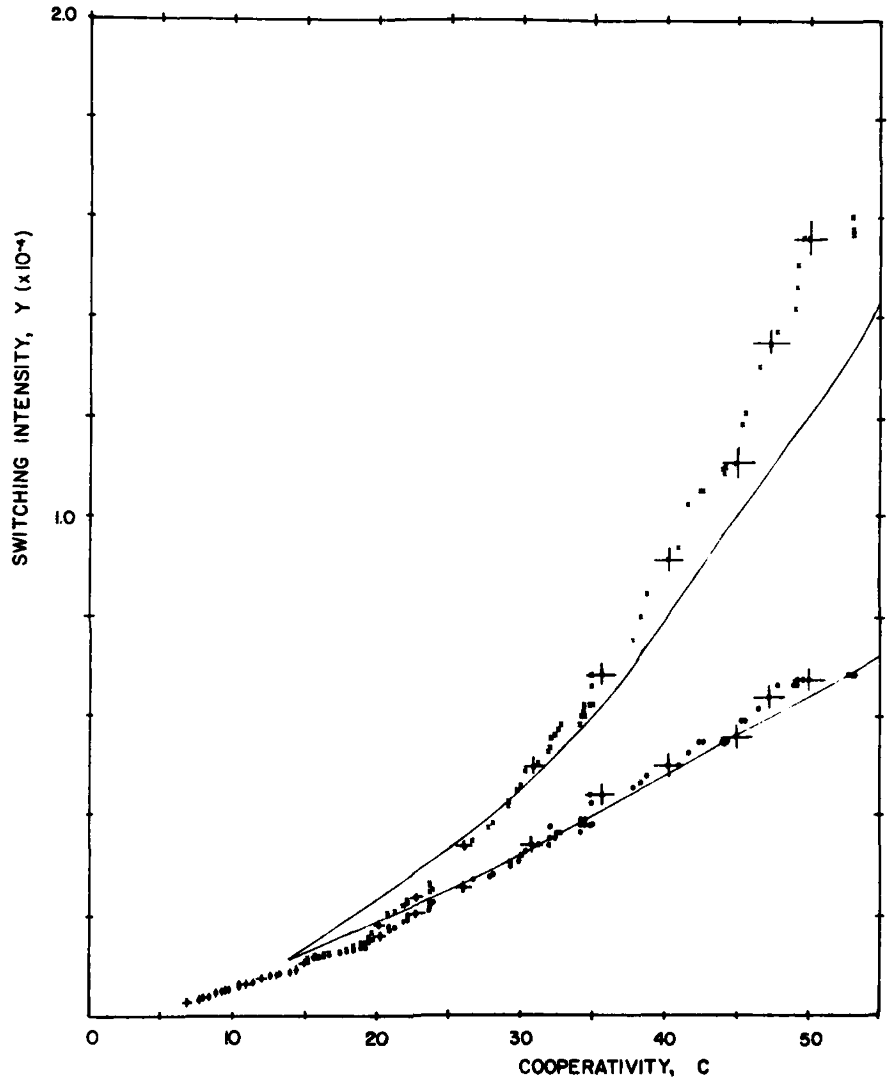

Figure 1. Incident laser intensity required to switch the bistable system (resonant cavity plus atomic beams) versus atomic cooperativity C. The region of the plot with two points in Y indicated for each value of C corresponds to the regime of bistable operation with two distinct switching points - one value of intensity causes a switch up and another a switch down. The data are normalized such that $Y=10^{4}$ corresponds to a cw power of 1.6×10^{-3} Watts incident upon the bistable resonator. The full curve is the theoretical result from reference 26.

IV. ELECTROMAGNETICS

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
ELECTROMAGNETICS

Research Unit EM81-1 GUIDED-WAVE DEVICES FOR THE FAR-INFRARED -MM WAVE SPECTRUM

Principal Investigators: Professor A.B. Buckman (471-4893)
Professor T. Itoh (471-1072)

Graduate Students: Yoshiro Fukuoka, Joe Haas, Doug Parse, Juan Rivera, Yi-Chi Shih, Karl Stephan, and Lingtao Wang

A. SCIENTIFIC OBJECTIVES: This work has as its overall objective the identification, analysis and, finally, the prototype demonstration of useful semiconductor wave-guide devices for production and control of radiation in the frequency range from ten to a few hundred gigahertz. This part of the spectrum is uniquely suited to a number of DoD needs, but its exploitation will require a mix of designs, some using concepts first developed in integrated optics, and others adapting microwave techniques. This research will focus on use of the Gunn and IMPATT mechanisms for radiation sources and on use of carrier injection and the field effect for electronic active guided wave devices such as modulators, active filters and beam deflectors. For the most part, the device concepts to be studied are compatible with planar waveguide integrated circuit technology.

B. PROGRESS:

(a) Gain Devices

The work performed in the previous period has resulted in description and characteristics of the gain mechanism in a distributed Gunn device made of a subcritically doped GaAs layer [1]. In accordance with the theory, we designed a coplanar type gain device. Double exposure masks have been developed and several devices fabricated at Hughes Aircraft Company. To date, two different substrate materials have been used. Both have an epitaxial layer of about 3μm grown on a semi-insulating substrate. Their doping levels are $n \approx 2 \times 10^{14}$ /cm^3 and 8×10^{14} /cm^3. Using an identical mask, coplanar devices have been made. The coplanar center strip is 7 μm wide, the strip-to-outer ground gap is 5 μm and the device length is about 5000 μm. Experimental results of the transfer characteristics are plotted in Fig. 1. Fig. 1(a) is for the $n \approx 2 \times 10^{14}$ /cm^3 device and (b) for $n \approx 8 \times 10^{14}$ /cm^3. It is clear from Fig. 1(a) that a gain mechanism arises from applying a bias. That is, the insertion loss decreases as compared to no loss bias case. Fig. 1(b) even shows a peak around 11 GHz. Such a peak in gain has been predicted by the theory in [1]. Unfortunately, both devices did not exhibit net device gain. The reason for this may be due to series resistance in the center electrode or to loss contribution from non-active portion of the device.

(b) Control Devices

(b.1) Schottky coplanar waveguide

It is known experimentally that there exist slow waves in a coplanar or microstrip transmission line created on a lossy semi-conductor substrate if one of the electrodes is Schottky contacted. The size of the depletion layer beneath the Schottky contact can be controlled by a DC bias, resulting in electronic control of the slow wave factor (phase delay).

Two analytical algorithms to analyze the wave phenomena in such coplanar structures have been developed independently. Accuracy of these algorithms have been studied by solving the MIS (metal-insulator-semiconductor) coplanar which also exhibits slow wave phenomena identical to the one in the Schottky structure. Numerical results by both methods agree well with each other and with the experimental data reported in [2], as seen in Fig. 2. In the mode matching analysis, the structure was assumed to be enclosed in a shield box to facilitate numerical processing. On the other hand, a structure with infinite dimensions has been handled by the spectral domain technique [3]. The increasing discrepancy between two methods at lower frequencies is caused by the presence and absence of this assumed shield box. Since we gained confidence in accuracy of the algorithms, we are applying them for Schottky structures. Two publications on this subject are under preparation.

(b.2) Coupled Mode Theory Analysis

It is convenient to develop a generalized coupled mode theory for open waveguide structures containing anisotropic, inhomogeneous media. The theory was developed for the purpose of analyzing a control device consisting of semiconductor and gyrotropic materials. The method has been applied for a proposed coupled structure made of dielectric and ferrite materials. The structure can be used as a distributed nonreciprocal device for extremely high millimeter-wave frequency application [4].

(b.3) Polarization and Mode Control

In earlier analytical work [5] we developed the concept of a three-layer dielectric waveguide polarizing structure. The device is all dielectric, all isotropic and promises to greatly relax the constraints of extinction ratio vs. insertion loss tradeoff which limit the usefulness of other polarizing structures. At optical frequencies, extinction raios approaching 10^4 are predicted, with insertion losses that might be as low as 0.1 db. In the 60-300 GHz range, losses will be determined by material properties, but very high extinction ratios are still possible. Recently we have developed physical insight into the operation of this three-layer waveguide, and have extended the concept to selection from among modes of the same polarization [6]. The physical mechanism of operation is a perturbation of the overlap of the field profile with the refractive index profile, which will either raise or lower the local propagation constant along the waveguide axis, depending on the mode. In general, any mode can be selected if control of refractive index and thickness during fabrication is sufficiently precise.

(c) Miscellaneous

(c.1) Directive Excitation of an Image Guide

The active devices studied under (A) will eventually be coupled to a planar waveguide. One method developed here is to use a Yagi-Uda array concept in which several parasitic elements are added to one active element so that the generated energy is directed into a specified direction. This concept was tested with a standard microwave generator and an image guide. Slot elements were created on the ground plane of the image guide. Measured results showed more than 10 db improvement in the directivity [7].

(c.2) Comparison of Waveguides

Various waveguides for millimeter-wave application have been compared with respect to frequency characteristics, ease of accommodating devices, etc. This study is relevant to the projects under (A) and (B) when actual implementation of the devices is eventually contemplated [8].

C. FUTURE DIRECTIONS:

(1) It is planned to use GaAs materials with different doping levels for gain devices. We will also investigate the effect of electrode thickness as well as that of geometries other than coplanar in which the field is more concentrated in the active region. Examples of possible geometries include the film structure and the rib structure. The metallorganic chemical vapor deposition system will be improved by incorporating a palladium-purified H_2 source and in-situ glow-discharge substrate precleaning. This should allow the growth of uniform single crystal GaAs films large enough to use in prototype devices.

(2) We will extend the analysis by the algorithms developed for Schottky contact coplanar lines to various depletion region sizes and geometrical dimensions. We plan to compare the results with some data provided by Hughes Aircraft Company.

(3) We will apply the transverse resonance technique for layered waveguide structures which include anisotropic or inhomogeneous media. This technique can facilitate finding an optimum structure.

(4) We plan to construct and test 60 GHz prototypes of the three-layer dielectric waveguide polarizer and mode selector, and to verify our theoretical predictions of extinction ratio and insertion loss.

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(Page 6, Res. Unit EM81-1 "Guided-Wave Devices for the Far-Infrared -mm Wave Spectrum")

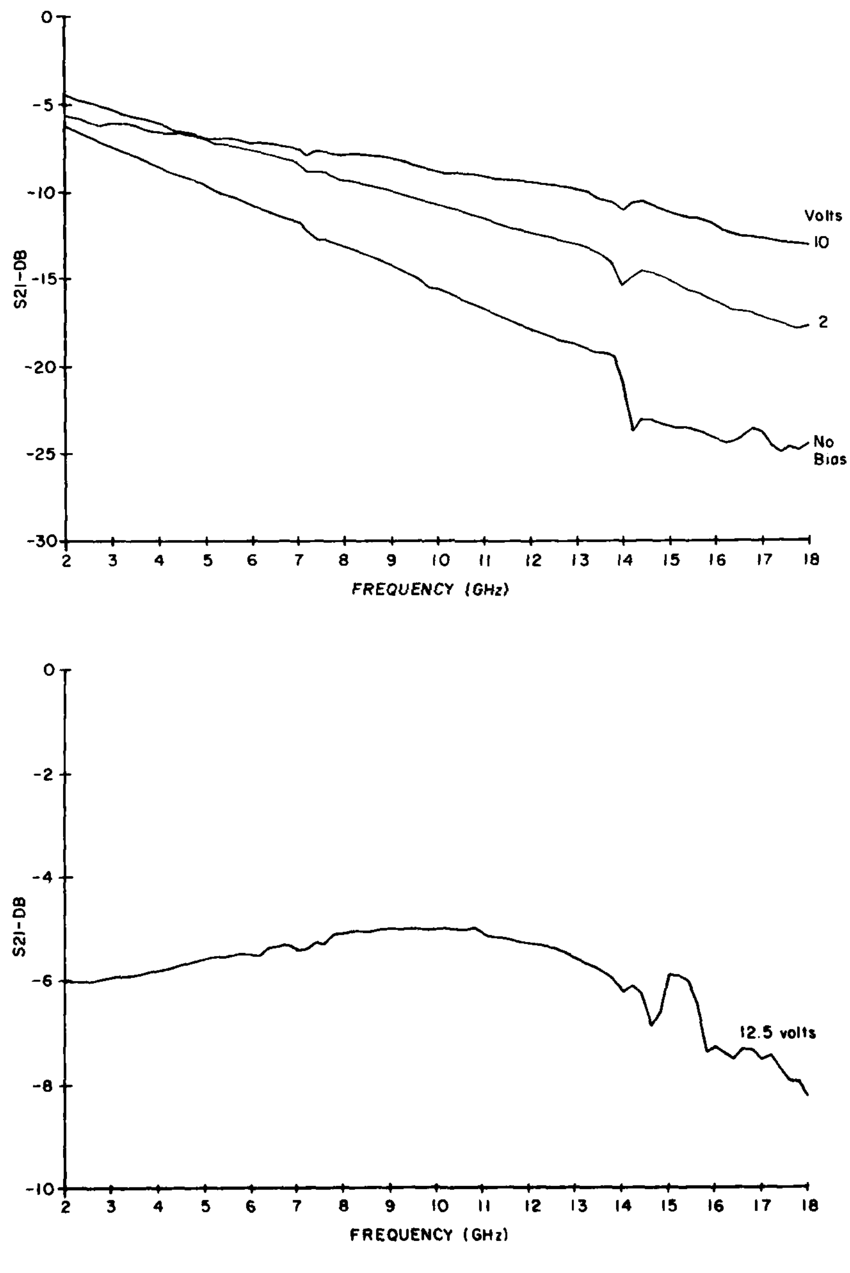

Fig. 1 Transfer characteristics of distributed Gunn devices (a) $n = 2 \times 10^{14}\ cm^{-3}$, (b) $n = 8 \times 10^{14}\ cm^{-3}$

(Page 7, Res. Unit EM81-1 "Guided-Wave Devices for the Far-Infrared -mm Wave Spectrum")

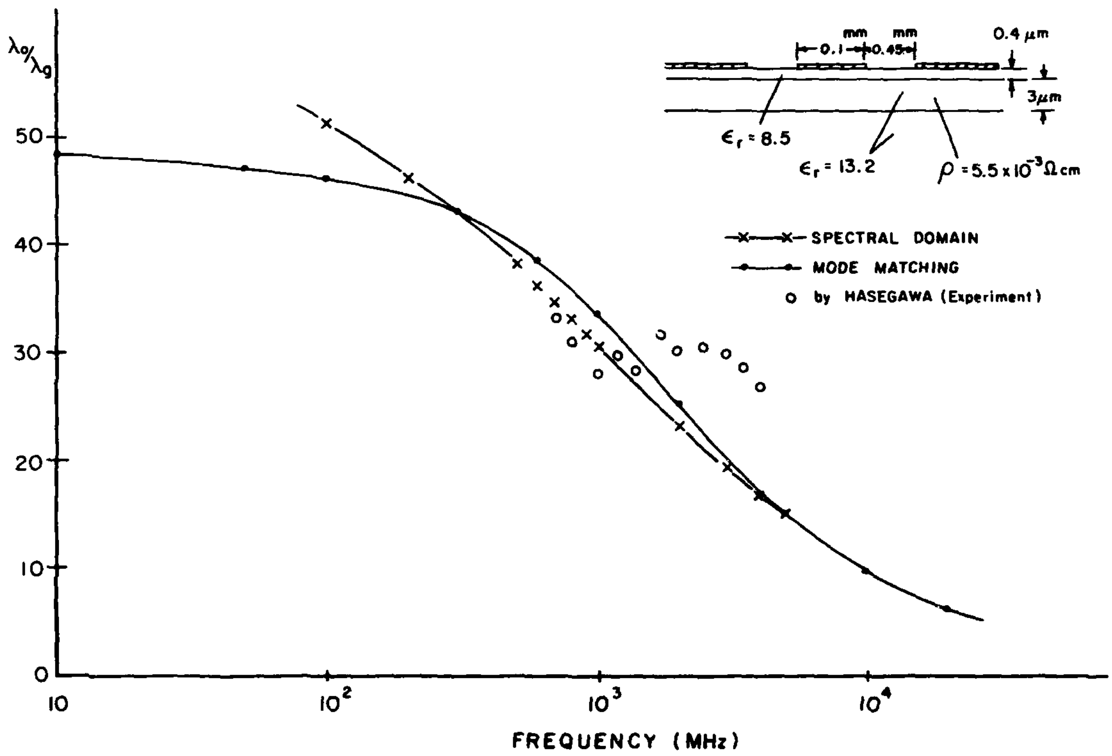

Fig. 2 Slow wave factor λ_0/λ_g of an MIS coplanar waveguide.

RESEARCH GRANTS AND CONTRACTS

RESEARCH GRANTS

FEDERAL FUNDS

Aerospace Medicine, Brooks Air Force Base, F33615-78-D-0629-0029, "Study of Radiofrequency Radiation Effects on Nonlinear Biprocesses," Professors Jason L. Speyer, Stephan E. Webber and Linda E. Reichl, Co-Principal Investigators, November 18, 1980 - August 15, 1981.

School of Aerospace Medicine, Brooks Air Force Base, Texas, "Radiofrequency Radiation and Nonlinear Biological Systems," Professors Jason L. Speyer, L.E. Reichl, S.E. Webber, R.A. Broucke, and I. Prigogine, Co-Principal Investigators, August 17, 1981 - December 21, 1981.

Department of Defense Joint Services Electronics Program Research Contract F49620-77-C-0101, "Basic Research in Electronics," Professor E.J. Powers, Principal Investigator on behalf of the Faculty Affiliates of the Electronics Research Center, April 1, 1977 - March 31, 1982.

Department of Energy, "Kinetic Studies Following State Selective Laser Excitation," Professor J.W. Keto, Principal Investigator, March 15, 1981 - March 14, 1983.

Armament Laboratory, Eglin Air Force Base, "Investigation of Information Enhancement, Estimation, and Guidance Algorithms for Homing Missile Guidance," Professor Jason L. Speyer and D.G. Hull, Co-Principal Investigators, October 1, 1981 - September 30, 1984.

National Science Foundation, MEA 78-00719, "Experiments on Nonlinear Interactions During the Transition to Turbulence," Professors R.W. Miksad and E.J. Powers, Co-Principal Investigators, November 1, 1978 - April 30, 1982.

National Science Foundation, ECS-7918246, "Periodic Optimal Control Theory," Professor Jason L. Speyer, Principal Investigator, November 1, 1979 - December 1, 1981.

National Science Foundation, CHE 80-07940, "Experimental Determinations of Charge Densities by Electron Diffraction," Professor M. Fink, Principal Investigator, July 1, 1980 - June 30, 1983.

National Science Foundation, CHE 80-05107, "Chemisorption and Catalysis on Well Characterized Metal Surfaces," Professor J.M. White, Principal Investigator, June 1, 1980 - November 1, 1981.

RESEARCH GRANTS

National Science Foundation, ECS-8022033, "Lie Algebraic Methods in Nonlinear Estimation," Professor S.I. Marcus, Principal Investigator, March 15, 1981 - August 31, 1983.

National Science Foundation, ECS-8111616, "Investigation of Excess ("1/F") Noise and Dielectric Response of Non-Crystalline Structures Preceeding First Nucleation in Thin Film Systems," Professor R.W. Bene', Principal Investigator, November 15, 1981 - April 30, 1983.

National Science Foundation, DMR 8106049, "High-Resolution Electron Energy Loss Spectrometer," Professor J.L. Erskine, Principal Investigator, September 1, 1981 - February 28, 1983.

National Science Foundation, DMR 7923629, "Experimental Studies of Intrinsic Surface Electronics Properties," Professor J.L. Erskine, Principal Investigator, July 1, 1982 - June 30, 1983.

National Science Foundation,DMR 8113088, "Research Grade Ion Implantation Instrument," Professors R.M. Walser and H.L. Marcus, Co-Principal Investigators, March 15, 1981 - January 31, 1983.

National Science Foundation, ECS 8 802-1511, "Computational Models for Processing Sequences of Bioengineering Images," Professor J.K. Aggarwal, Principal Investigator, May 1, 1981- October 31, 1982.

Office of Naval Research, Contract N00014-75-C-10922, "Structure and Reactivity in Catalytic Systems Involving Metal Oxides and Electrode Surfaces," Professor J.M. White, Principal Investigator, August 1, 1980 - July 31, 1981.

Office of Naval Research, Contract N00014-79-C-0553, "Studies of Non-Reciprocal Effects in Planar Submillimeter to Optical Waveguiding Structures," Professor T. Itoh, Principal Investigator, June 1, 1980 - August 31, 1983.

Office of Naval Research, Contract N00014-75-C-0916, "Synthesis of Useful Electronic Structures Using Solid-Solid Phase Reactions Near Surfaces," Professors R.W. Bene' and R.M. Walser, Co-Principal Investigators, May 1, 1975 - April 30, 1981.

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U.S. Army Research Office, DAAG29-78-G-0146, "Quasi-Optical Techniques for Millimeter and Submillimeter-Wave Circuits," Professor T. Itoh, Principal Investigator, July 1978 - October 31, 1980.

U.S. Air Force Armament Technology Laboratory, F08635-81-K-0101, "Measurement of Aerodynamic Transfer Functions Utilizing Novel Digital Time Series Analysis Techniques," Professors Edward J. Powers and Ronald O. Stearman, Co-Principal Investigators, June 19, 1981 - June 19, 1982.

U.S. Air Force Armament Technology Laboratory, F08635-80-K-0350, "Homing Missile Guidance Based Upon Filter Observability Enhancement," Professors Jason L. Speyer and David Hull, Co-Principal Investigators, October 1980 - September 1981.

U.S. Air Force Office of Scientific Research, AFOSR 78-3712, "New Nonlinear Optical Processes in Molecules at Infrared Frequencies," Professor M.F. Becker, Principal Investigator, October 1, 1978 - December 31, 1981.

U.S. Air Force Office of Scientific Research AFOSR 79-0025, "Optimal and Suboptimal Estimation for Nonlinear Stochastic Systems," Professor S.I. Marcus, Principal Investigator, December 1, 1978 - November 30, 1982.

U.S. Army Research Office, DAAG29-81-K-0053, "Interface Structures for Millimeter-Wave Circuits," Professor T. Itoh, Principal Investigator, March 1, 1981 - February 29, 1984.

U.S. Air Force Office of Scientific Research, AFOSR 77-3190, "Automatic Recognition and Tracking of Objects," Professor J.K. Aggarwal, Principal Investigator, December 1, 1976 - November 30, 1981.

U.S. Air Force Office of Scientific Research, 82-0064, "Automatic Recognition and Tracking of Objects," Professor J.K. Aggarwal, Principal Investigator, December 1, 1981 - November 30, 1982.

U.S. Air Force Office of Scientific Research AFOSR 80-0154, "High Resolution Electron Energy Loss Studies of Chemisorbtion Species of Aluminum and Titanium," Professor J.L. Erskine, Principal Investigator, April 1, 1982 - March 31, 1983.

RESEARCH GRANTS

OTHER THAN FEDERAL FUNDS

General Dynamics, "Redundancy Management for Fault Tolerant Flight Control Systems," Professors J.L. Speyer and D.G. Hull, Co-Principal Investigators, May 1, 1981 - December 31, 1981.

Motorola, Inc. and Bell Telephone Laboratories, Inc., Equipment Grant to create semiconductor device fabrication facility, Professor A.B. Buckman, Principal Investigator, 1980 - 1982.

Research Corporation, "Momentum Transfer in Resonance Fluorescence," Professor H.J. Kimble, Principal Investigator, June 12, 1980 - June 11, 1981.

Texas Atomic Energy Research Foundation, "Analysis and Interpretation of Plasma Fluctuation Data Utilizing Digital Time Series Analysis," Professor E.J. Powers, Principal Investigator, May 1, 1976 - April 30, 1982.

Texas Instruments, "Millimeter-Wave Transmission Lines Study," Professor T. Itoh, Principal Investigator, June 1, 1976 - December 31, 1982.

University of Texas Equipment Grant to create Kimble Lab, Professor H.J. Kimble, Principal Investigator, November 16, 1979 - August 31, 1981.

University of Texas Matching Funds from the Research Corporation Grant, Professor H.J. Kimble, Principal Investigator, June 12, 1980 - June 11, 1981.

University of Texas Equipment Grant to create Kimble Lab and expenses, Professor H.J. Kimble, Principal Investigator, September 1, 1979 - August 31, 1981.

University of Texas Research Instrumentation Grant, Professor R.M. Walser, Principal Investigator, January 18, 1982 - August 1, 1982.

Robert A. Welch Foundation, F-600, "Raman Spectroscopy of Van der-Waas Dimer and Collisional Molecular Complexes," Professor L. Frommhold, Principal Investigator, June 1, 1981 - May 31, 1983.

RESEARCH GRANTS

Robert A. Welch Foundation, F-788, "Coherent Raman Spectroscopy of Molecular Ions," Professor J.W. Keto, Principal Investigator, June 1, 1980 - May 31, 1983.

Robert A. Welch Foundation, F-222, "Interactions of Reactive Species with Surfaces," Professor J.M. White, Principal Investigator, June 1, 1980 - May 31, 1981.

Robert A. Welch Foundation, F534, "Electron Scattering from Alkali Halide Vapors," Professor M. Fink, Principal Investigator, June 1, 1980 - May 31, 1985.

Robert A. Welch Foundation, F-720, "Experimental Studies of Metal Surface Absorbates," Professor J.L. Erskine, Principal Investigator, June 1, 1981 - May 31, 1983.

Robert A. Welch Foundation, F-789, "Momentum Redistribution by Resonant Radiation," Professor H.J. Kimble," Principal Investigator, June 1, 1980 - May 31, 1983.

NEW DISCOVERIES, INVENTIONS OR PATENT DISCLOSURES

A proposed coupled-mode type millimeter wave isolator reported in the paper

> "Coupled-mode Theory Analysis of Distributed Nonreciprocal Structures," IEEE Trans. Microwave Theory and Techniques, vol. MTT-29, pp. 1077-1087, Oct. 1981

is currently being evaluated by Office of Naval Research Patent Counsel as a possible patentable invention. The work was in part supported by JSEP.

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A115 888
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) ANNUAL REPORT ON ELECTRONICS RESEARCH at The University of Texas at Austin No. 29	5. TYPE OF REPORT & PERIOD COVERED Annual Report for period 4/1/81 through 3/31/82
	6. PERFORMING ORG. REPORT NUMBER No. 29
7. AUTHOR(s) Edward J. Powers, Director; and other faculty and graduate research staff of the Electronics Research Center	8. CONTRACT OR GRANT NUMBER(s) Cont. F49620-77-C-0101
9. PERFORMING ORGANIZATION NAME AND ADDRESS Electronics Research Center The University of Texas at Austin Austin, Texas 78712	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2305/A9 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research (AFSC) AFOSR/NE Bolling AFB, D.C. 20332	12. REPORT DATE May 15, 1982
	13. NUMBER OF PAGES 123
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Approved for public release; distribution unlimited

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

INFORMATION ELECTRONICS
SOLID STATE ELECTRONICS
QUANTUM ELECTRONICS
ELECTROMAGNETICS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes progress on projects carried out at the Electronics Research Center at The University of Texas at Austin and which were supported by the Joint Services Electronics Program. In the area of Information Electronics progress is reported for projects involving (1) nonlinear detection and estimation and (2) electronic multi-dimensional signal processing.

In the Solid State Electronics area recent findings in (1) interface reactions, instabilities and transport and (2) spectroscopic studies of metal/semiconductor and metal/metal oxide interfaces are described.

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In the area of Quantum Electronics progress is presented for the following projects: (1) nonlinear wave phenomena, (2) structure and kinetics of excited state molecules, and (3) collective effects in nonlinear optical interactions.

In the Electromagnetics area progress in guided-wave devices for the far infrared-mm device spectrum is summarized.